NEW

UNDERSTANDING Meteorology

HUNTING HURRICANES
DOUBLE RAINBOWS
THE SMELL OF RAIN
FIRESTORMS
CLOUD-SPOTTING
CLIMATE CHANGE

Digital Edition

FUTURE
FIRST EDITION

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Welcome

The weather affects us all. Whether it's something as small as deciding if we should wear a sun hat or raincoat, or as big as preparing for an incoming tornado or battling the effects of climate change, it's important to understand how and why these things happen. What are sunrays made from? Why are rain clouds grey? How do snowflakes form? Can we control storms? What will happen if we don't reduce the impacts of climate change? In this brand-new special edition, we've compiled a selection of articles from How It Works to explain the science behind these questions and answer everything you ever wanted to know about meteorology.

Disclaimer:
The information in this book was correct at the time of original publication, but may have changed since.

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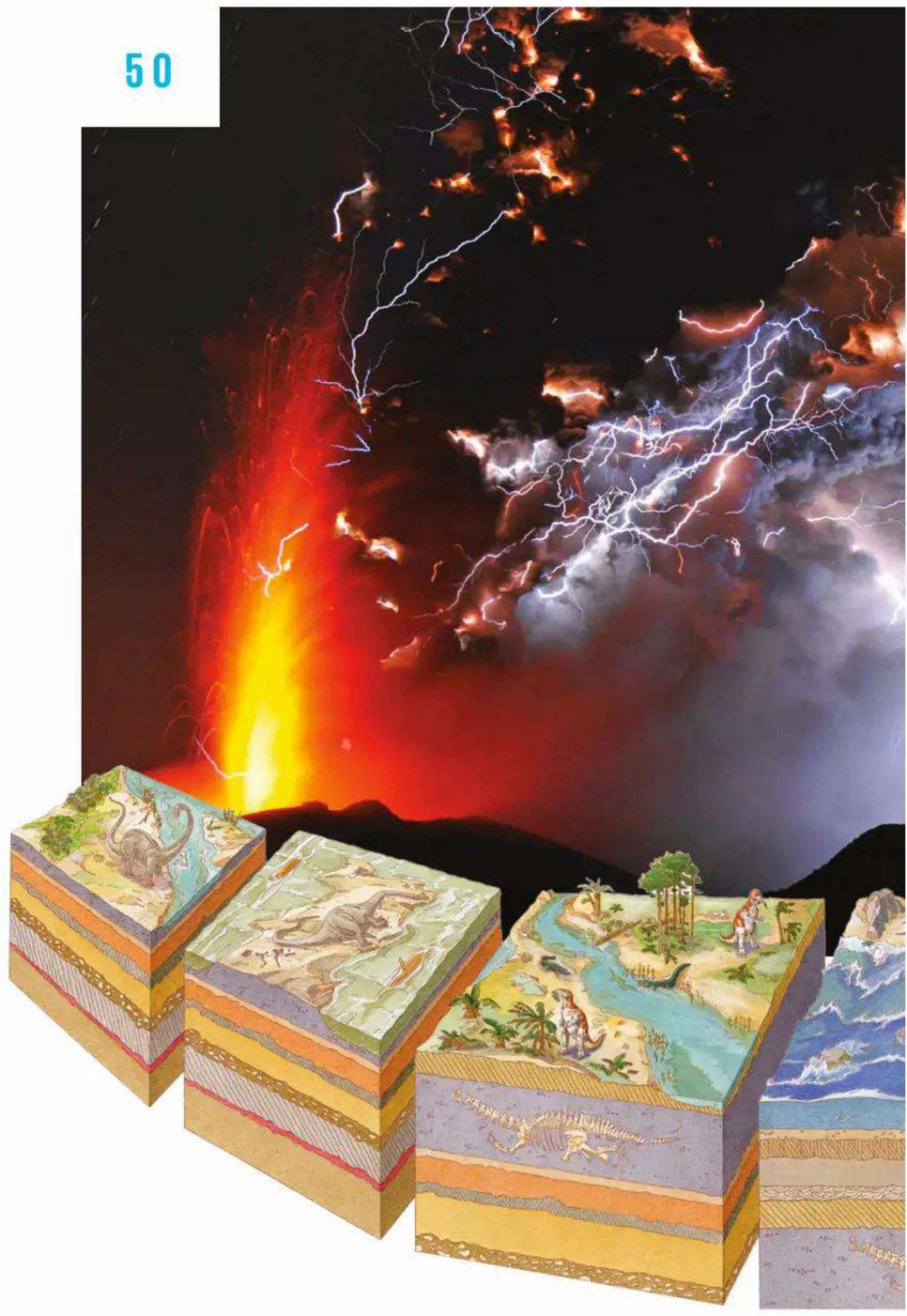

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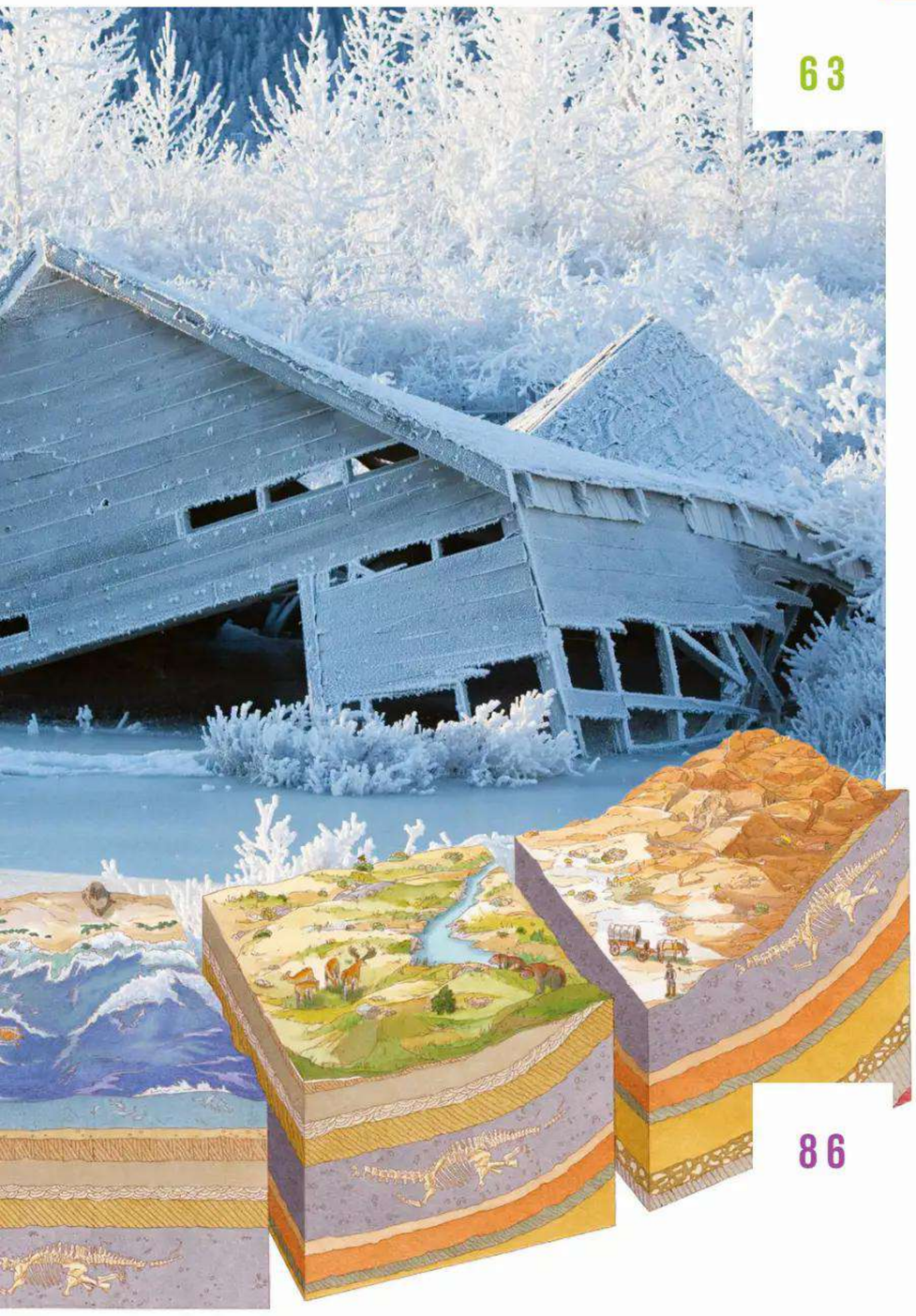

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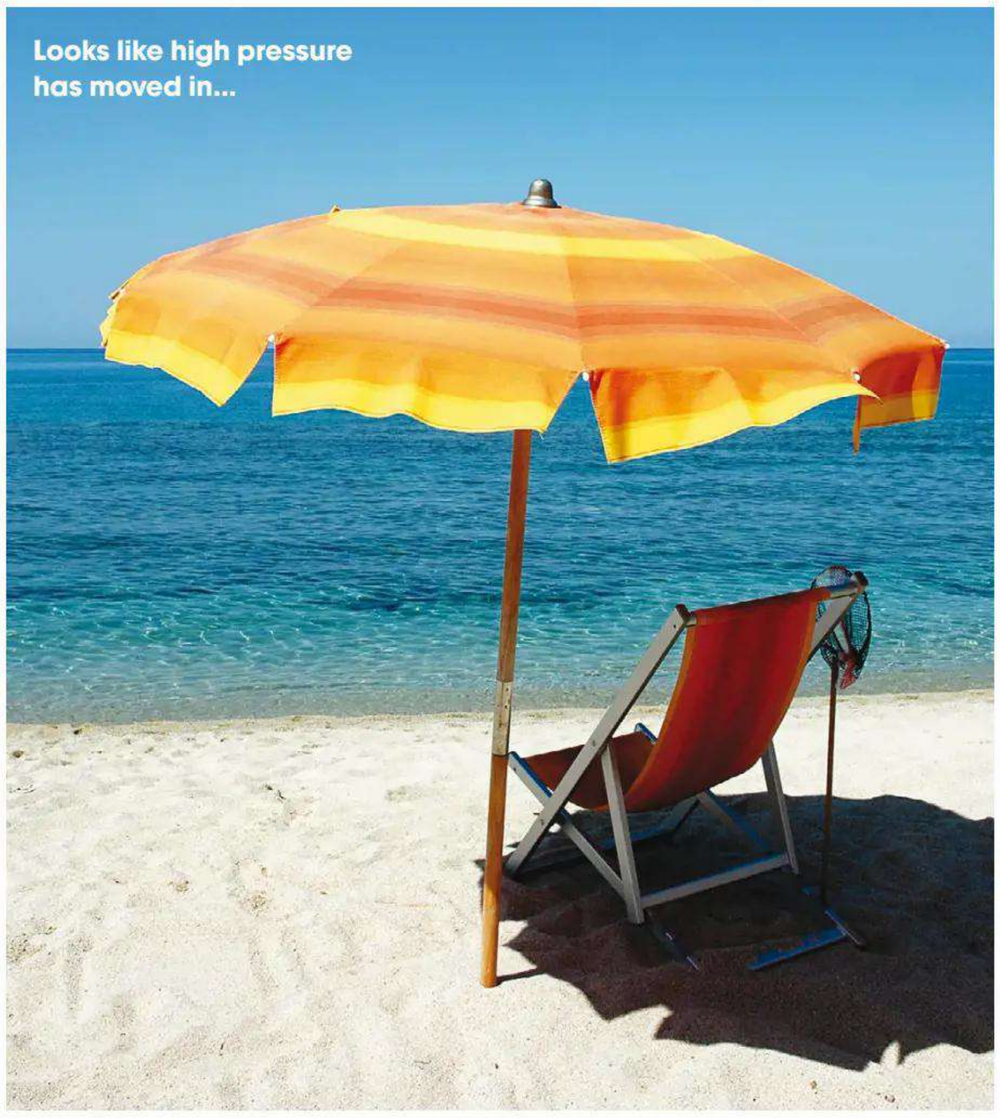
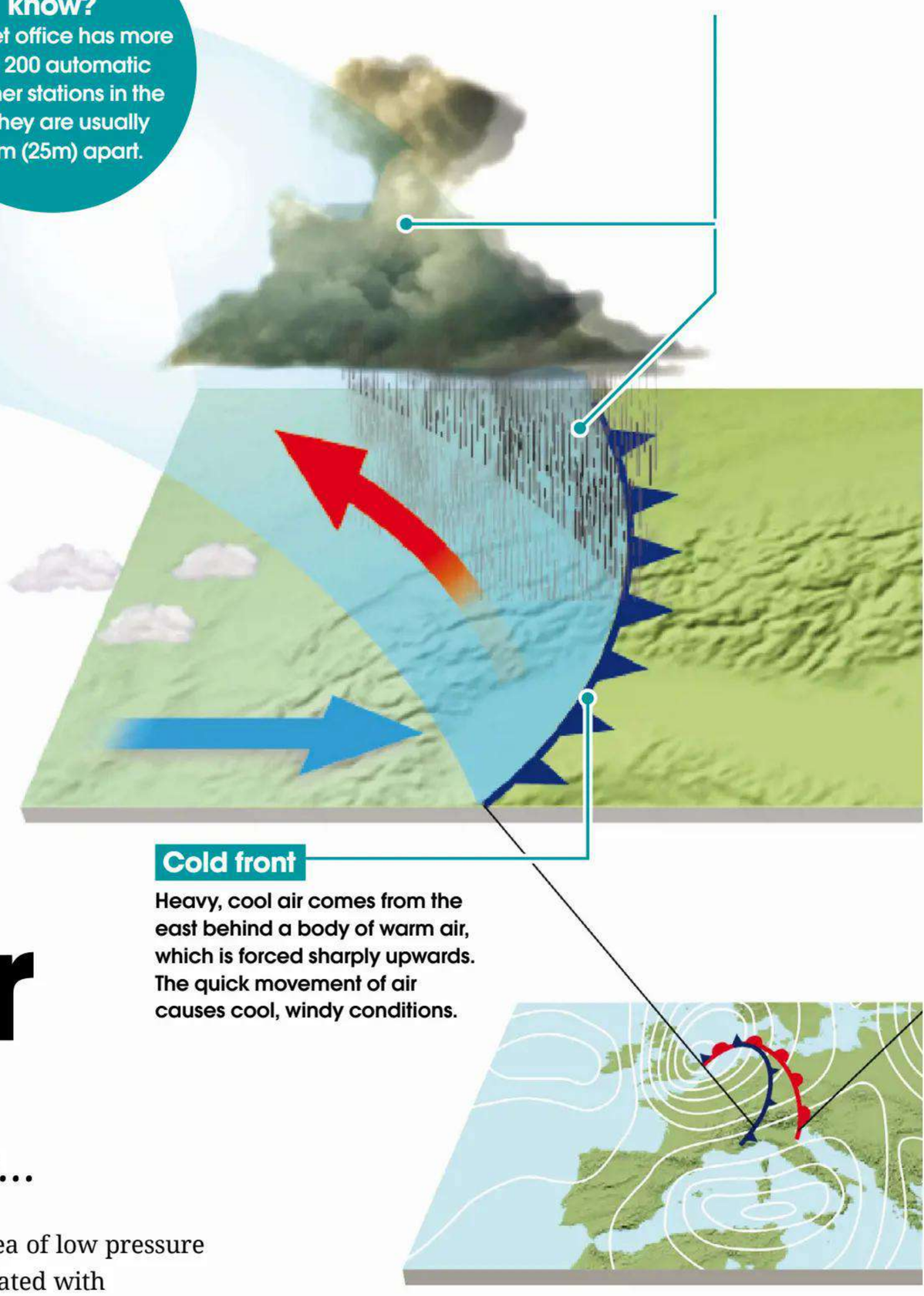

Looks like high pressure has moved in...

Did you know?
The Met office has more than 200 automatic weather stations in the UK; they are usually 40km (25m) apart.

Cold front conditions

As the warm air is forced upwards so quickly, when it cools and condenses it forms cumulonimbus clouds and therefore heavy rain or thunderstorms. Cumulus clouds follow on from this, with showery conditions and eventually clear skies.



Predicting the weather

To take an umbrella or not? How we get those all-important forecasts...

Weather is unpredictable. So how is it that we can gather information and make predictions about what conditions on Earth will be like?

Most weather phenomena occur as a result of the movement of warm and cold air masses. The border between these bodies of air are known as 'fronts', and it's here that the most exciting weather, including precipitation and wind, occurs.

As a body of air passes across different types of terrain – such as over the oceans, low-lying areas or even mountainous regions – air temperature and moisture levels can change dramatically. When two air masses at different temperatures meet, the less dense, warmer of the two masses rises up and over the colder. Rising warm air creates an area of low pressure (a depression), which is associated with unsettled conditions like wind and rain.

We know how a frontal weather system will behave and which conditions it will produce down on the ground. Norwegian meteorologist Vilhelm Bjerknes first brought the idea of frontal weather systems to the fore in the early 20th century. Through his constant observation of the weather conditions at frontal boundaries, he discovered that numerical calculations could be used to predict the weather. This model is still used today.

Since the introduction of frontal system weather forecasting, the technology to crunch the numbers involved has advanced immeasurably, enabling far more detailed analysis and prediction. In order to forecast the weather with the greatest accuracy, meteorologists require vast quantities of weather data – including temperature, precipitation, cloud coverage, wind speed and wind direction – collected from weather stations located all over the world. Readings are taken constantly and fed via computer to a central location.

Technology is essential to both gathering and processing the data about the conditions down on Earth and in the upper atmosphere. A supercomputer, for example, is capable of predicting the path and actions of hurricanes and issuing life-saving warnings. Using data collected by monitors and sensors, it can complete billions of calculations per second to produce imagery that can reveal how the hurricane is expected to develop.

Warm and cold fronts

What do these terms mean and how do they affect us?

In practice

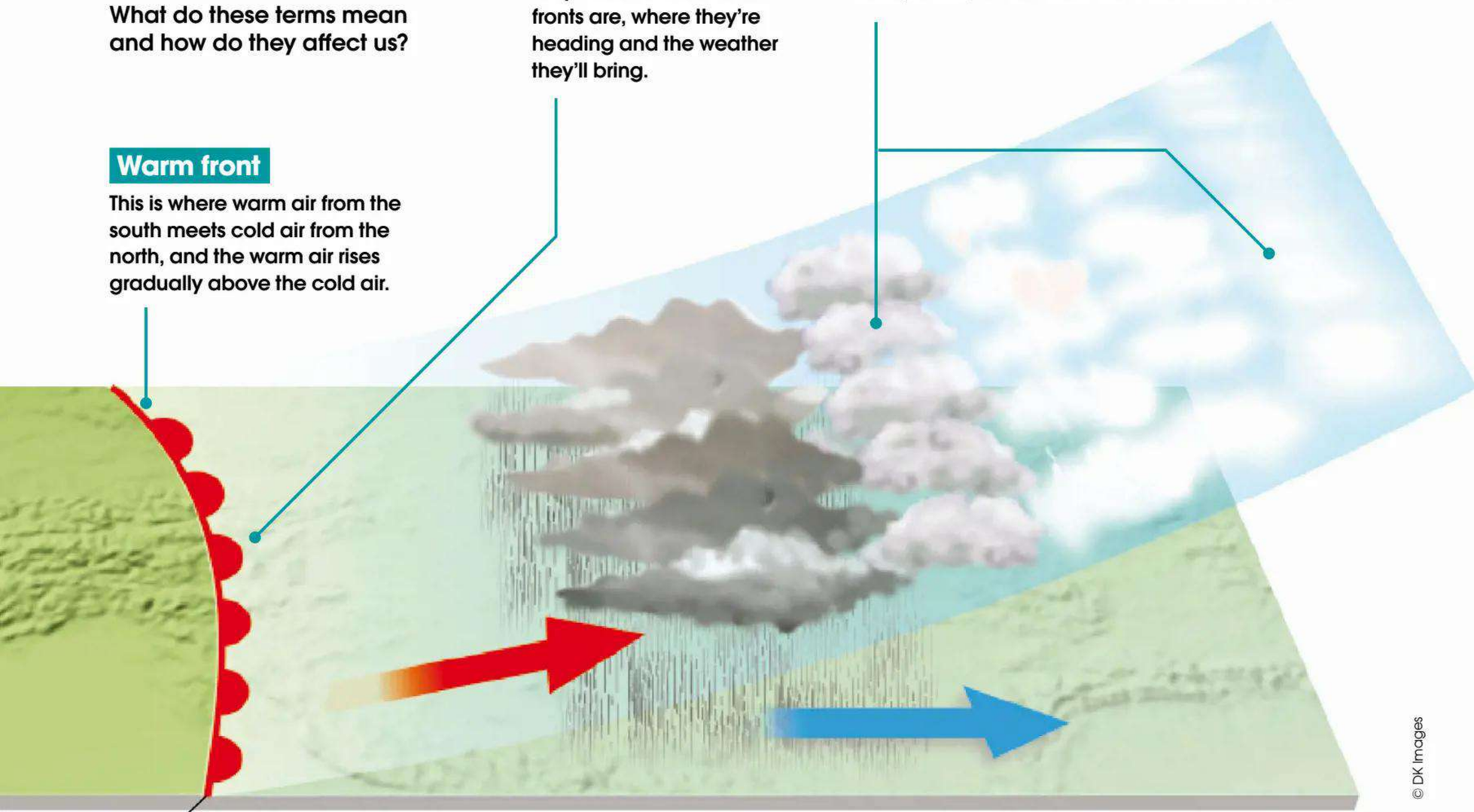
The red curves of a warm front and blue triangles of a cold front are shown on a map to show where the fronts are, where they're heading and the weather they'll bring.

Warm front conditions

As the warm air slowly rises, it cools and condenses and clouds are formed. These are nimbostratus, causing steady rainfall, then altostratus accompanied by drizzle, and finally cirrus, when clearer skies can be seen.

Warm front

This is where warm air from the south meets cold air from the north, and the warm air rises gradually above the cold air.



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Weather forecast map

Learn what these weather-related signs and symbols mean

High pressure

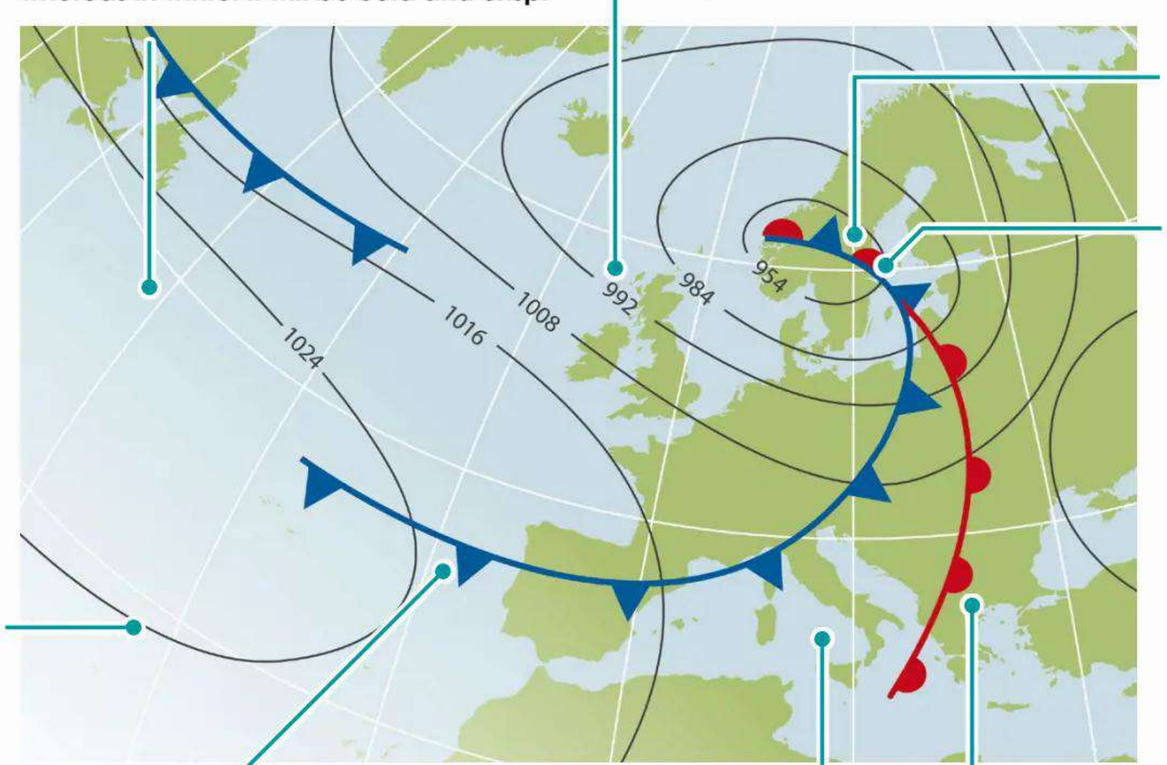
Weather here will be clear and dry, due to the high pressure. If this high pressure occurs in summer weather will be warm, whereas in winter it will be cold and crisp.

Wind

The conditions at this point will be windy. This is indicated by the position of the isobars; the closer together they are the windier the conditions.

Low pressure

At the centre of these circular patterns of isobars is where systems of high or low pressure lie. Where there is low pressure conditions it will be rainy and windy.



Isobars

These indicate atmospheric pressure. Areas of equal atmospheric pressure are joined together with the lines shown and the numbers indicate pressure measured in millibars. Lower numbers indicate low pressure, while higher numbers indicate high pressure.

Occluded front

This is where one front 'catches up' with another. In this example, the cold has caught up with the warm. Occluded fronts cause the weather to change quickly and, in this case, become similar to that of a cold front.

Cold front

As with any cold front, the weather here will be expected to be cool with heavy rainfall and possibly even thunderstorms. This will be followed by showers.

In between

After the passing of the warm front and before the arrival of the cold front conditions should be clear and dry, but normally only for a short period.

Warm front

The warm front will cause steady rainfall, followed by drizzle, accompanied by cloudy skies. These are typical conditions caused by any warm front.

Fronts

A weather front is the line on a map dividing two air masses of different densities. Here conditions will be unsettled. The symbols for fronts are arranged on lines consisting of semicircles, triangles or a mixture of the two.

Cold front

Associated with brief episodes of severe weather, and identified by a blue line with triangles that point in the direction of movement, a cold front marks the leading edge of an advancing mass of cold air. Because cold air is denser, it pushes the warmer air up where it condenses into clouds and precipitation. Dense cold air also travels faster than warm.

Warm front

Slower-moving warm fronts are marked on weather maps as a red line with semicircles that point in the direction of movement. These represent the leading edge of an advancing mass of warm, moist air, bringing with it cloud, precipitation and warm temperatures.

Occluded front

This purple line of alternating triangles and semicircles denotes an occluded front, or occlusion, which forms when the faster-moving cold front catches up with the warm front, forcing the less-dense warm air up above the surface.

Stationary front

These stationary, or slow-moving fronts represent the boundary between two air masses neither of which has the ability to replace the other. Stationary fronts are depicted by an alternating line of red semicircles and blue triangles pointing in opposite directions. Clouds and prolonged precipitation are associated with these fronts.

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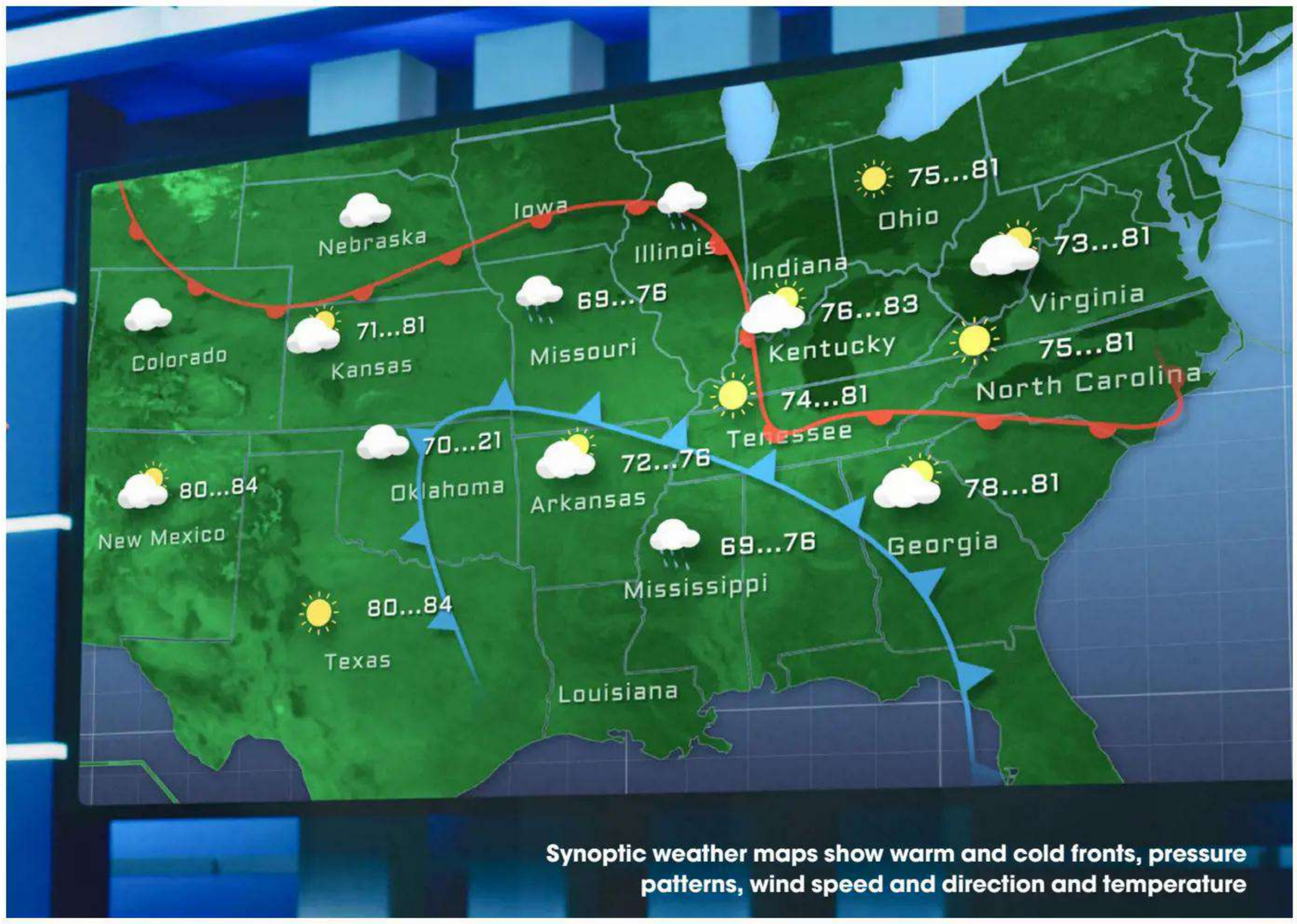
Weather symbols

How to read and understand the symbols on a weather map

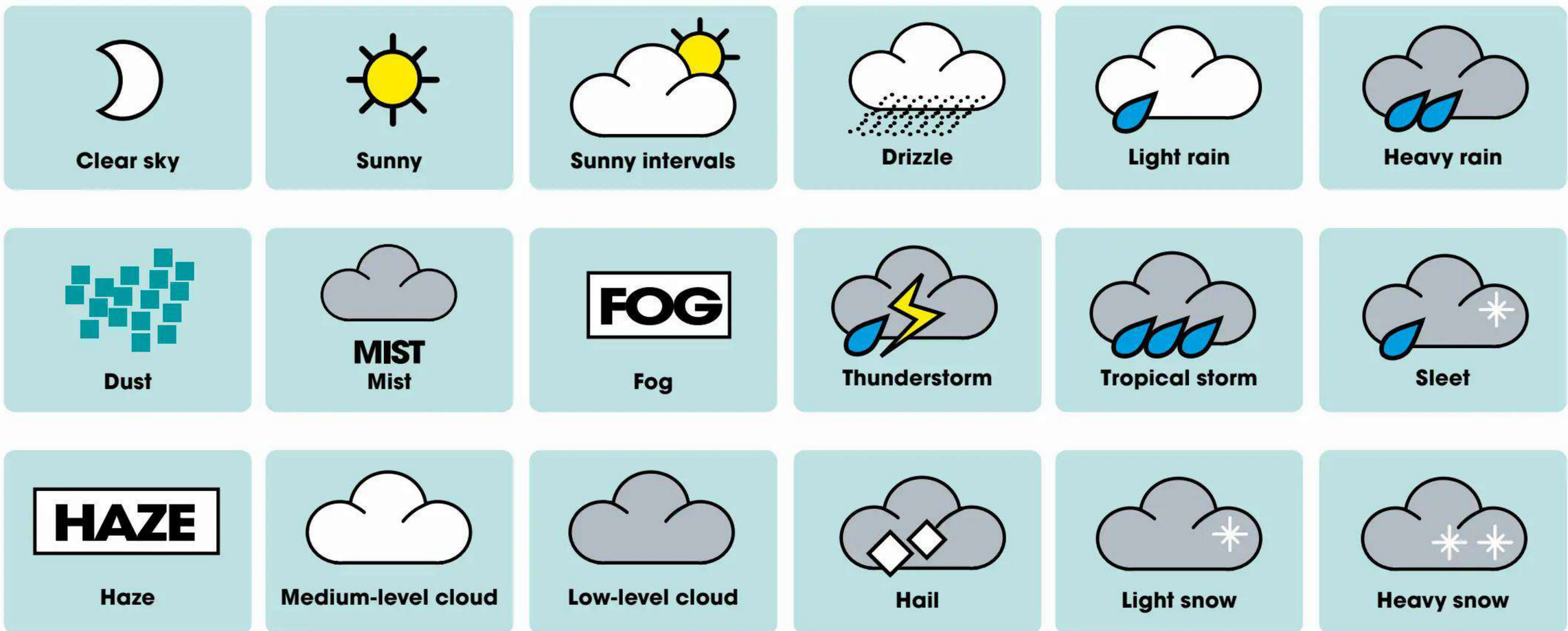
Weather forecast centres around the world are constantly analysing atmospheric conditions on Earth. The public are then supplied with this information in the form of pictographic maps detailing precipitation, cloud, wind speed/direction, temperature, and frontal systems. Have you ever watched the weather update on the news and wondered what all the symbols on the weather map mean other than just sunny or raining? Below you'll find a more detailed view of weather symbols. Use them to decipher the next weather map you read.



Synoptic weather maps show warm and cold fronts, pressure patterns, wind speed and direction and temperature

Types of weather

The other symbols found on a weather map include the various types of weather. The following classification symbols are based on those the Met Office uses. There are additional symbols for day and night variations...



Temperature

Temperature is shown as a figure (measured in degrees Fahrenheit or degrees Celsius) depicted either by a number in a circle/square, or as an isotherm, which is a line linking points of equal temperature.

Wind

Wind also features a figure that shows wind speed in miles per hour. This number is accompanied by an arrow to indicate which direction the wind is travelling.

Pressure

Atmospheric pressure is shown in the form of isobars, which are lines of equal mean sea-level pressure. When there is a difference in air pressure, air is accelerated from high to low pressure, causing windy conditions.

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Weather monitoring

Discover the method that helps us prepare for the elements, come rain or shine

The weather affects us all, every day. From governing the difference between life and death, to providing a conversation topic to fill awkward silences at a party, it is an ever-present and ever-changing part of life. This means that predicting it accurately is a hugely important task.

In the UK, the Met Office is responsible for weather monitoring and prediction. Before a forecast can be put together, measurements from thousands of data recorders across the world are collected and analysed. Every day, around 500,000 observations are received, including atmospheric measurements from land and sea, satellites, weather balloons and aircraft. But, this is still not enough to represent the weather in every location.

To fill in the gaps, the data is assimilated. This combines current data with what is expected, to provide the best estimate of the atmospheric conditions. To produce an accurate forecast, the data has to be fed into a supercomputer that creates a numerical model of the atmosphere. The process involves many complex equations, and the Met Office's supercomputer can perform 16,000 trillion calculations a second, running an atmospheric model with more than a million lines of code.

Did you know?
Weather balloons can reach altitudes of 40km (25mi).

Forecasters can use this data and techniques such as nowcasting – using estimates of current weather speed and direction – to predict the weather in the hours ahead. For longer range forecasts, further computer models are relied upon.

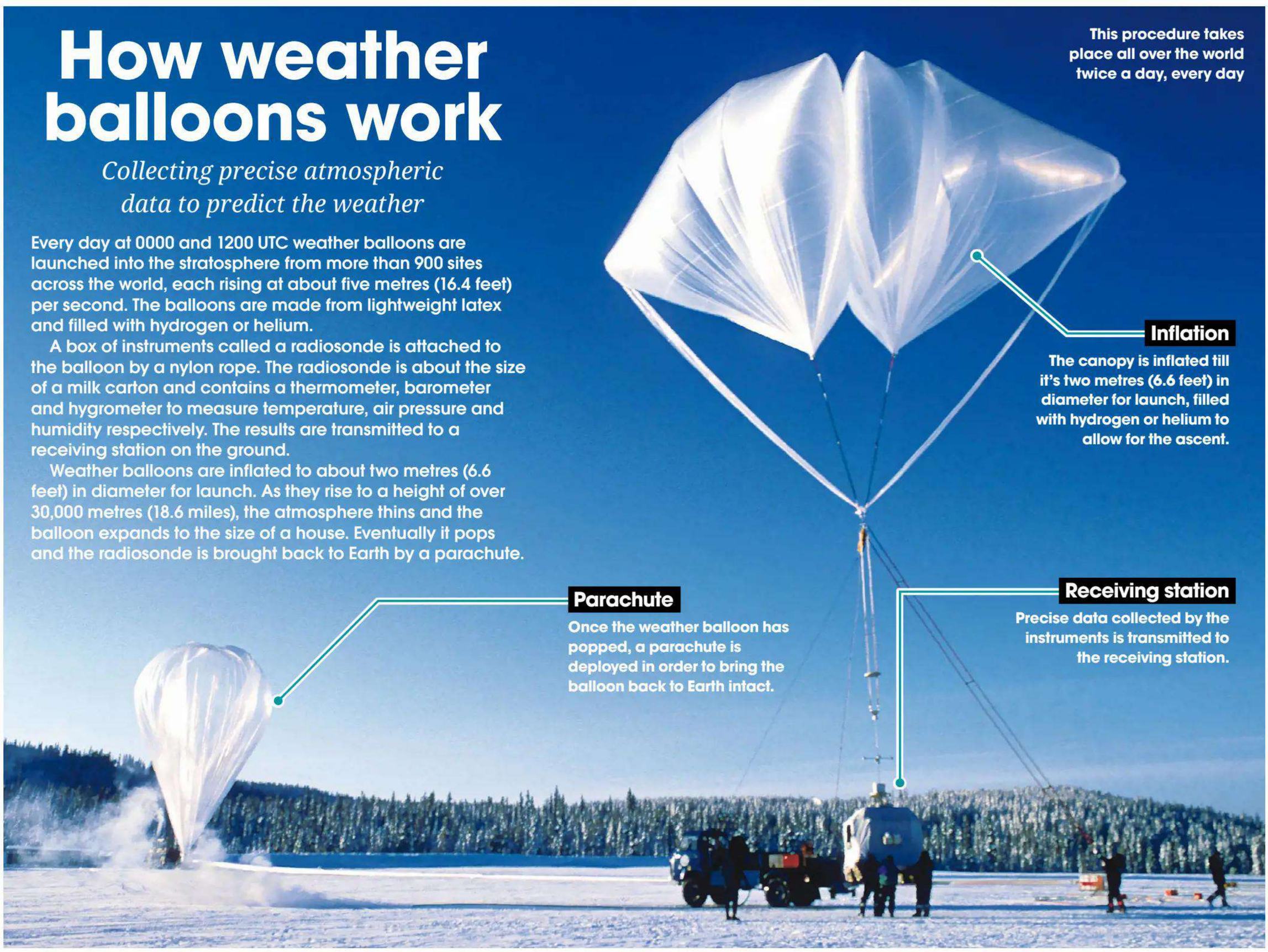
How weather balloons work

Collecting precise atmospheric data to predict the weather

Every day at 0000 and 1200 UTC weather balloons are launched into the stratosphere from more than 900 sites across the world, each rising at about five metres (16.4 feet) per second. The balloons are made from lightweight latex and filled with hydrogen or helium.

A box of instruments called a radiosonde is attached to the balloon by a nylon rope. The radiosonde is about the size of a milk carton and contains a thermometer, barometer and hygrometer to measure temperature, air pressure and humidity respectively. The results are transmitted to a receiving station on the ground.

Weather balloons are inflated to about two metres (6.6 feet) in diameter for launch. As they rise to a height of over 30,000 metres (18.6 miles), the atmosphere thins and the balloon expands to the size of a house. Eventually it pops and the radiosonde is brought back to Earth by a parachute.



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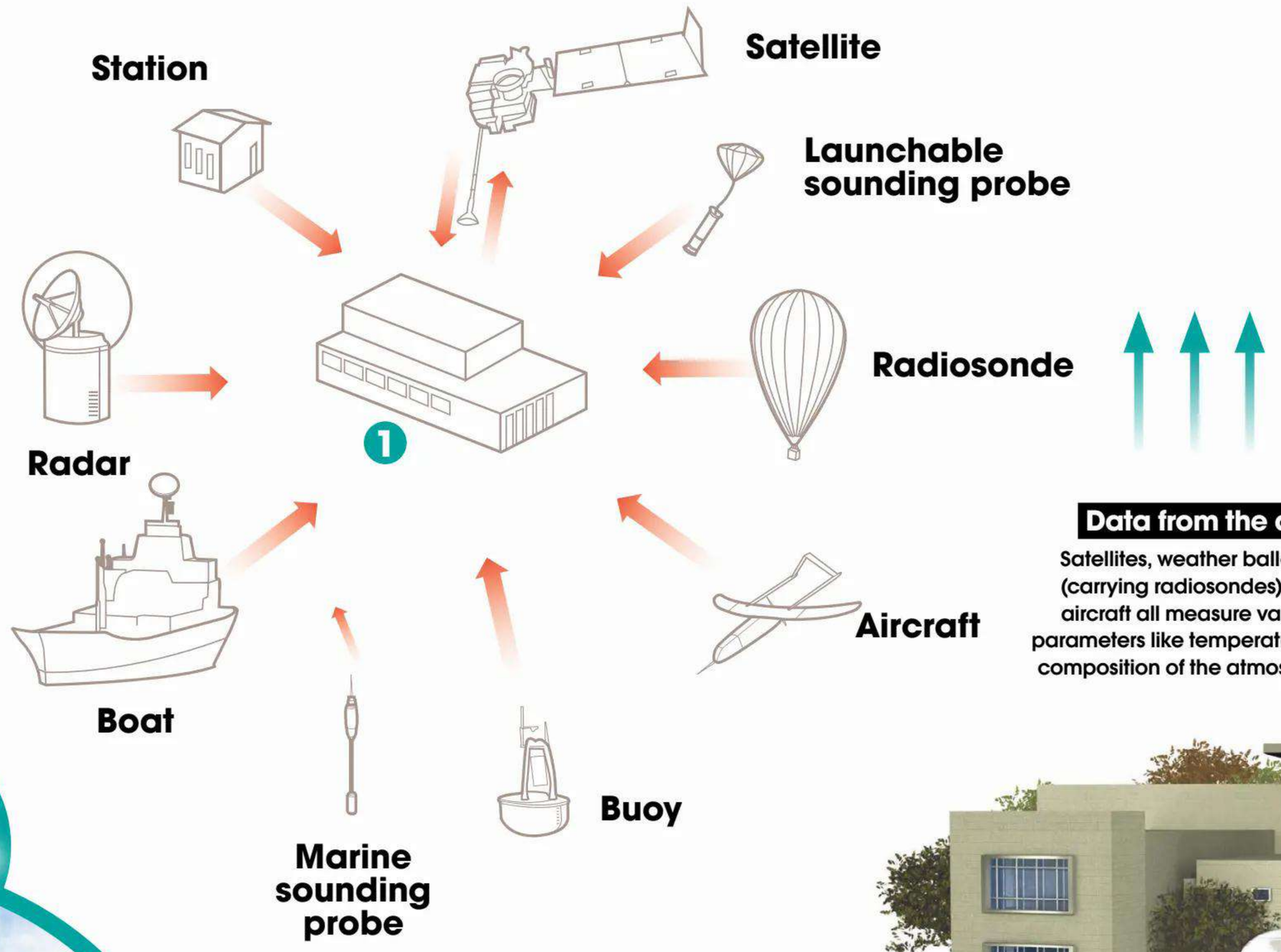
Collecting weather data

Discover how the world gathers information to predict the weather

1 Data collection
Data from receivers all over the world is transmitted to a variety of hubs such as the World Meteorological Organization in Switzerland.

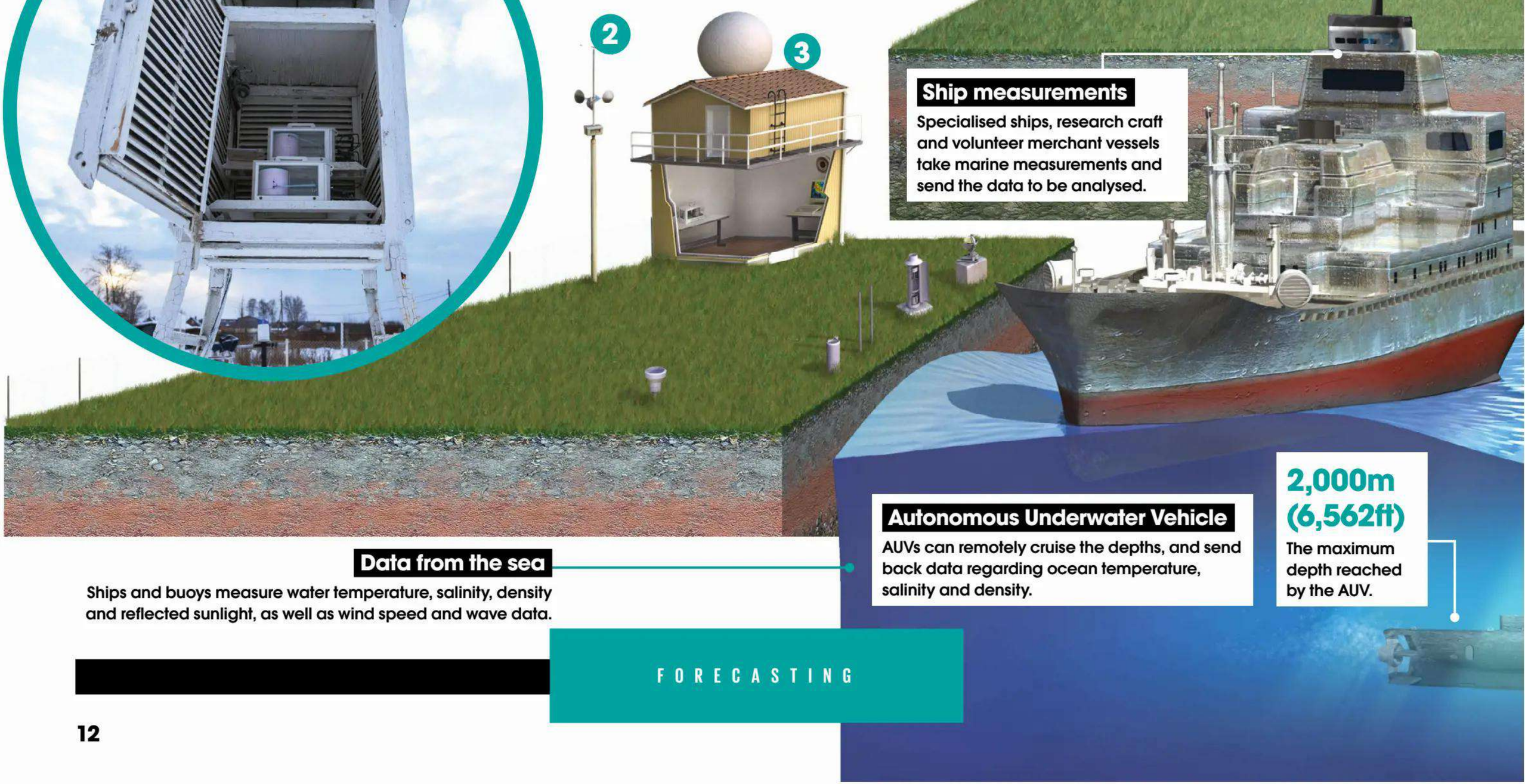
2 Land-based data
Instruments on land measure temperature, atmospheric pressure, humidity, wind speed and direction, cloud cover, visibility and precipitation.

3 Meteorological station
Small weather stations take local readings, with thermometers for temperature, hygrometers for humidity and barometers to measure atmospheric pressure.



Data from the air
Satellites, weather balloons (carrying radiosondes) and aircraft all measure various parameters like temperature and composition of the atmosphere.

Thousands of small weather stations across the world feed data back to meteorological hubs.



Ship measurements
Specialised ships, research craft and volunteer merchant vessels take marine measurements and send the data to be analysed.

Data from the sea
Ships and buoys measure water temperature, salinity, density and reflected sunlight, as well as wind speed and wave data.

Autonomous Underwater Vehicle
AUVs can remotely cruise the depths, and send back data regarding ocean temperature, salinity and density.

2,000m (6,562ft)
The maximum depth reached by the AUV.

4 Radiosonde
This small instrument is attached to a helium or hydrogen balloon and takes airborne measurements of pressure, temperature and humidity.

15,000m (9.3mi)
The altitude reached by a radiosonde.

13,000m (8mi)
The altitude reached by G-IV aircraft, which drop sounding probes towards the ground.

10,000m (6.2mi)
The altitude at which specialist meteorological aircraft can reach.

4,270m (2.6mi)
The altitude reached by the P-3 aircraft.

365m (0.2mi)
The altitude reached by an aerosonde drone.

Satellites
Geostationary and polar orbiting satellites record data and produce imagery to show forecasters fog coverage, cloud height and precipitation.

Meteorological aircraft
Data comes from either specialist meteorological planes, or from the automatic recordings of commercial flights.

Launchable sounding probe
Dropped from an aircraft, this probe can measure wind velocity, temperature, humidity and pressure as it falls.

Hurricane hunters
These modified Lockheed P-3 Orion aircraft, are equipped with state-of-the-art instruments, and a highly sensitive Doppler radar.

Doppler radar

Jet G-IV

Parachutes prolong airtime

Radiosonde sends information to base

The future of forecasting
New modelling techniques that account for changes in humidity, temperature, wind velocity and cloud activity could make forecasting more accurate.

Current model

Scale: 12km (7.4mi) per slide

Experimental model

Strongest winds

Scale: 1.3km (0.8mi) per slide

Aerosonde
This unmanned research craft is capable of sampling and recording weather data swiftly and accurately.

Meteorological centres
All of the data recorded is assimilated in these centres, as well as being analysed and distributed for more local predictions.

"Every day, around 500,000 observations are received from land and sea"

Navigation lights

Anemometer

Data transmitter

Solar panel

Weather buoys
Either tethered or free-floating, buoys are furnished with instruments to take meteorological measurements where ships can't or don't go.

Maritime sounding probes
Dropped from aircraft into the sea, these probes are often called 'dropsondes' and can sample and transmit data back to base.

Radar station
Radar is used in meteorology to measure the intensity with which rain, snow, sleet or hail is falling.

© Sol 90; Thinkstock

The atmosphere

The Earth's atmosphere

It's all around us, but how much do we know about our atmosphere?

Our atmosphere (made up of 78 per cent nitrogen and 21 per cent oxygen, with other gases making up the last per cent) is held in place by gravity and consists of a number of different layers that work together to protect us from solar radiation and to keep consistent temperatures. The atmosphere gets thinner with altitude, with 80 per cent of its mass in the first layer closest to the Earth's surface. There are five main layers that make up the atmosphere. The troposphere is the first layer (and is where our weather occurs), followed by the stratosphere, mesosphere, thermosphere and exosphere. There is no definite boundary between where the atmosphere ends and outer space begins, though the Kàrmàn line at 100 kilometres (62 miles) above sea level is often regarded as one.

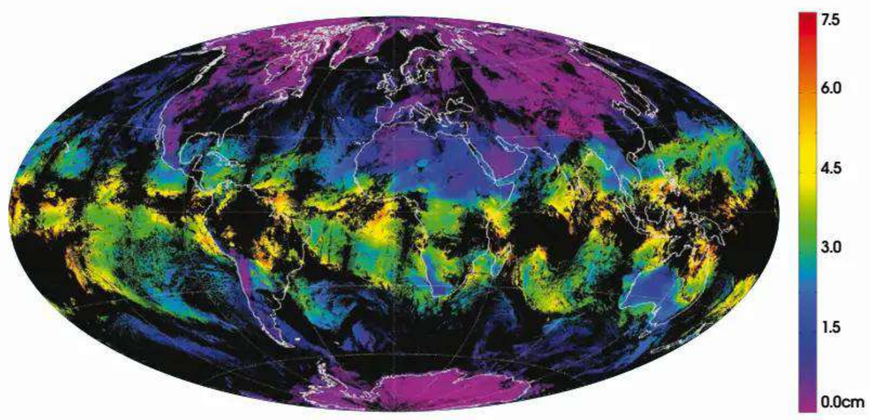
There are other layers that exist. The lowest of these is the 'planetary boundary', which is within the troposphere and closest to the Earth's surface and its depth can vary widely between 100 metres to 3,000 metres (328 feet to 1.86 miles) as it is directly affected by conditions on the surface. The ozone layer is contained within the stratosphere, in its lower portion. Around 90 per cent of the ozone in the atmosphere lies here. The ionosphere is what causes auroras, such as the northern lights, as it is ionised by solar radiation and stretches from 50 to 1,000 kilometres (31 to 621 miles), overlapping the exosphere and thermosphere.

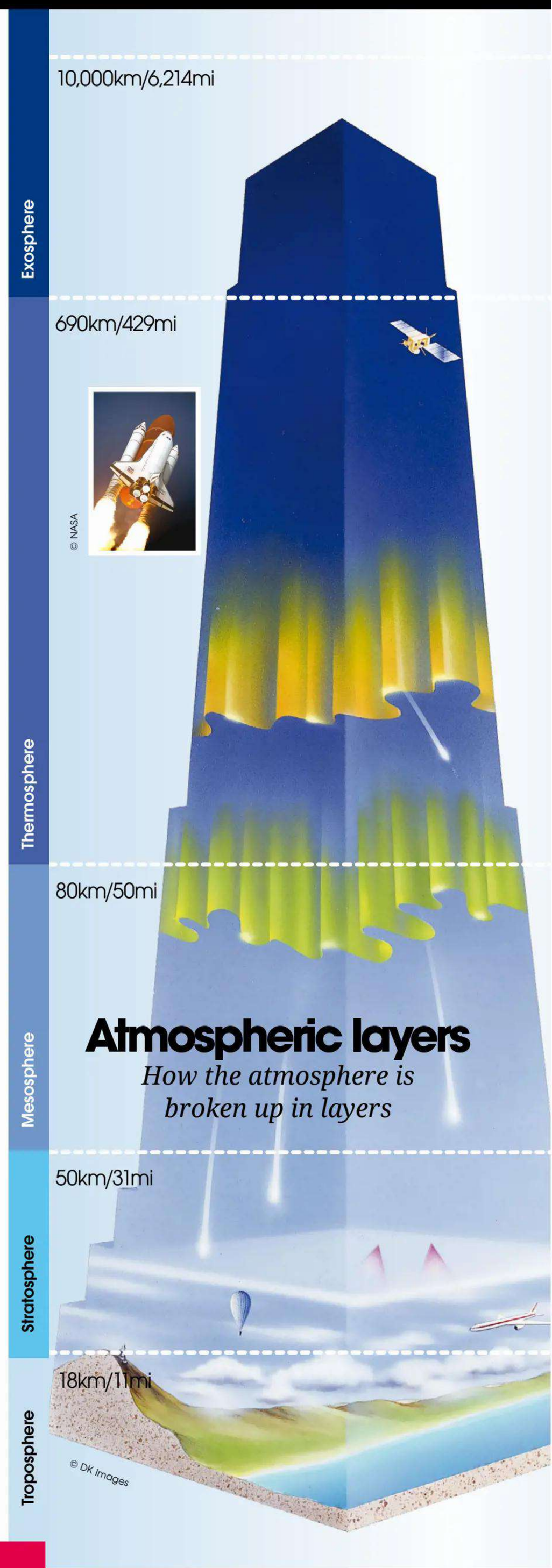
Finally, the homosphere and the heterosphere run from the Earth's surface to around 80 kilometres (50 miles) and from 80 kilometres upwards respectively. They are so-named because of the way the gases within them are mixed. The heterosphere has a chemical composition that changes with height, whereas the homosphere's make-up remains more constant. The five main layers are based on the thermal structure of the atmosphere, whereas the additional layers are classified according to composition.

The northern lights are caused partly by the atmosphere

Atmospheric water vapour

The gaseous water vapour in our atmosphere is responsible for our rain, snow, hail, fog, and clouds. If the vapour was to fall evenly over the planet as precipitation, each year 25mm (1in) of water will have fallen.



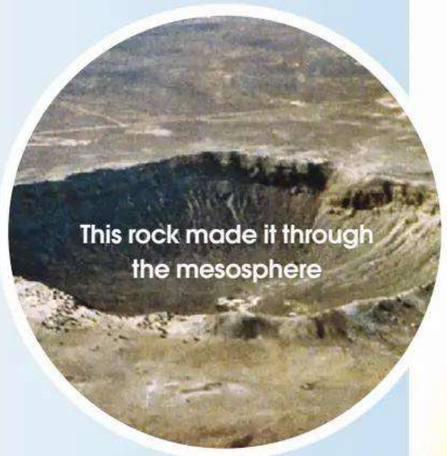


Atmospheric layers

How the atmosphere is broken up in layers

5 Exosphere
The final layer where particles are widely spaced and can travel hundreds of kilometres/miles before colliding with another particle. The makeup of this layer is mainly hydrogen and helium.

4 Thermosphere
Temperatures start to increase with height. This is also the layer in which the International Space Station orbits, between 320km (199mi) and 380km (236mi). It extends up to the base of the exosphere, called the exobase.


This rock made it through the mesosphere

3 Mesosphere
Extends from the stratopause (again, the layer boundary) to a height of 80-85km (50-53mi) and is notably the layer in which meteors burn up when entering the atmosphere. Temperatures decrease with height, and in the mesopause is the coldest place on Earth (around -100°C/-148°F).

2 Stratosphere
Starts from the tropopause (the boundary between the first two layers) up to around 51km (32mi), with temperatures increasing with height. This is where you'll find things like weather balloons.

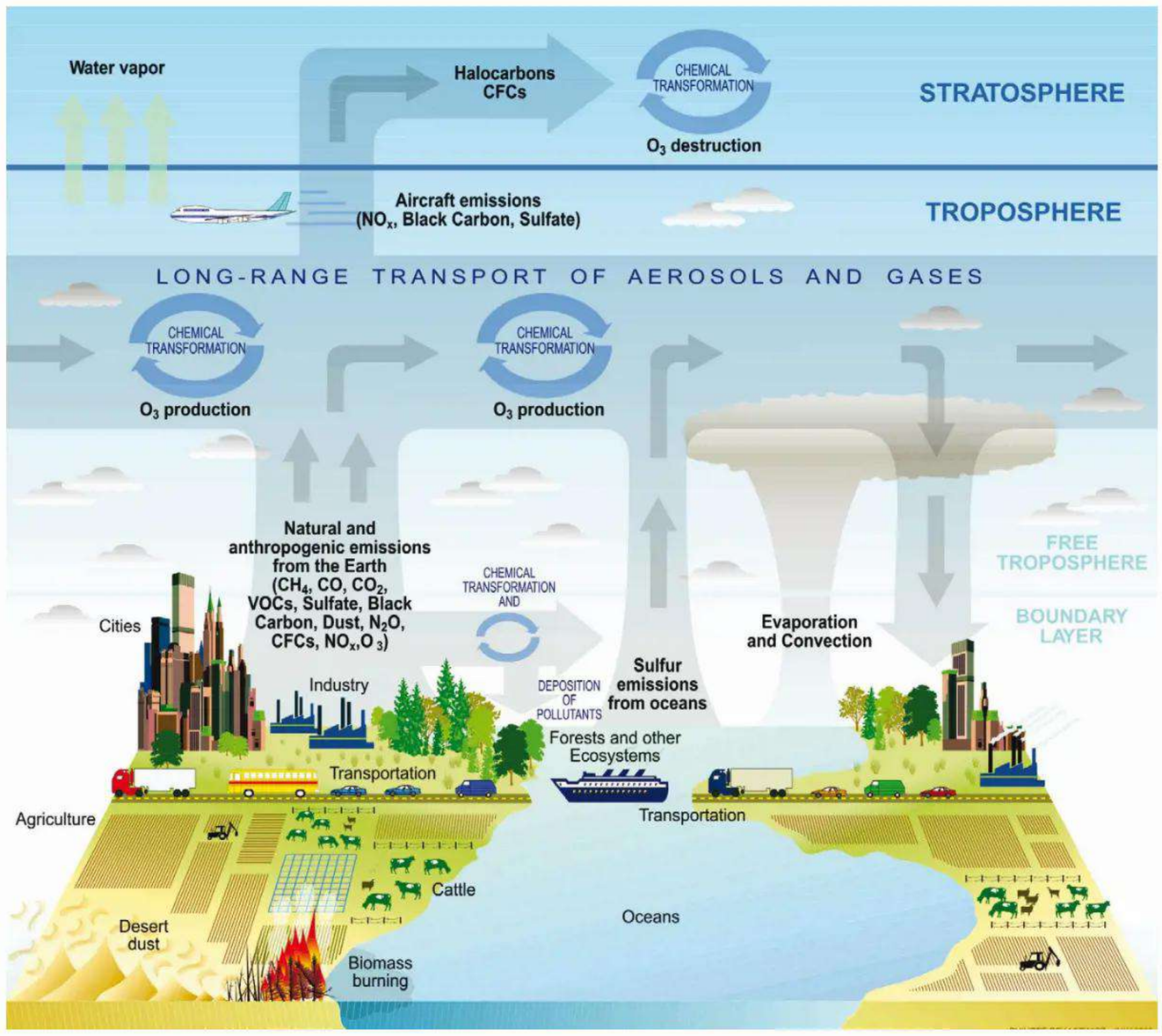
1 Troposphere
The first layer, starting at the Earth's surface and extending to between 7km and 17km (4 and 10.5mi). It is heated by a transfer of energy from the Earth's surface, so it gets cooler as it goes higher.

Pollution in the air

The effects of pollution include smog, acid rain, the greenhouse effect, and holes in the ozone layer. Each problem has implications for both our health and the environment.

The carbon dioxide gas produced when fuel is burned may contribute to the greenhouse effect. Plants can convert CO2 back to oxygen, but the human production of CO2 currently exceeds the amount the plants can convert back.

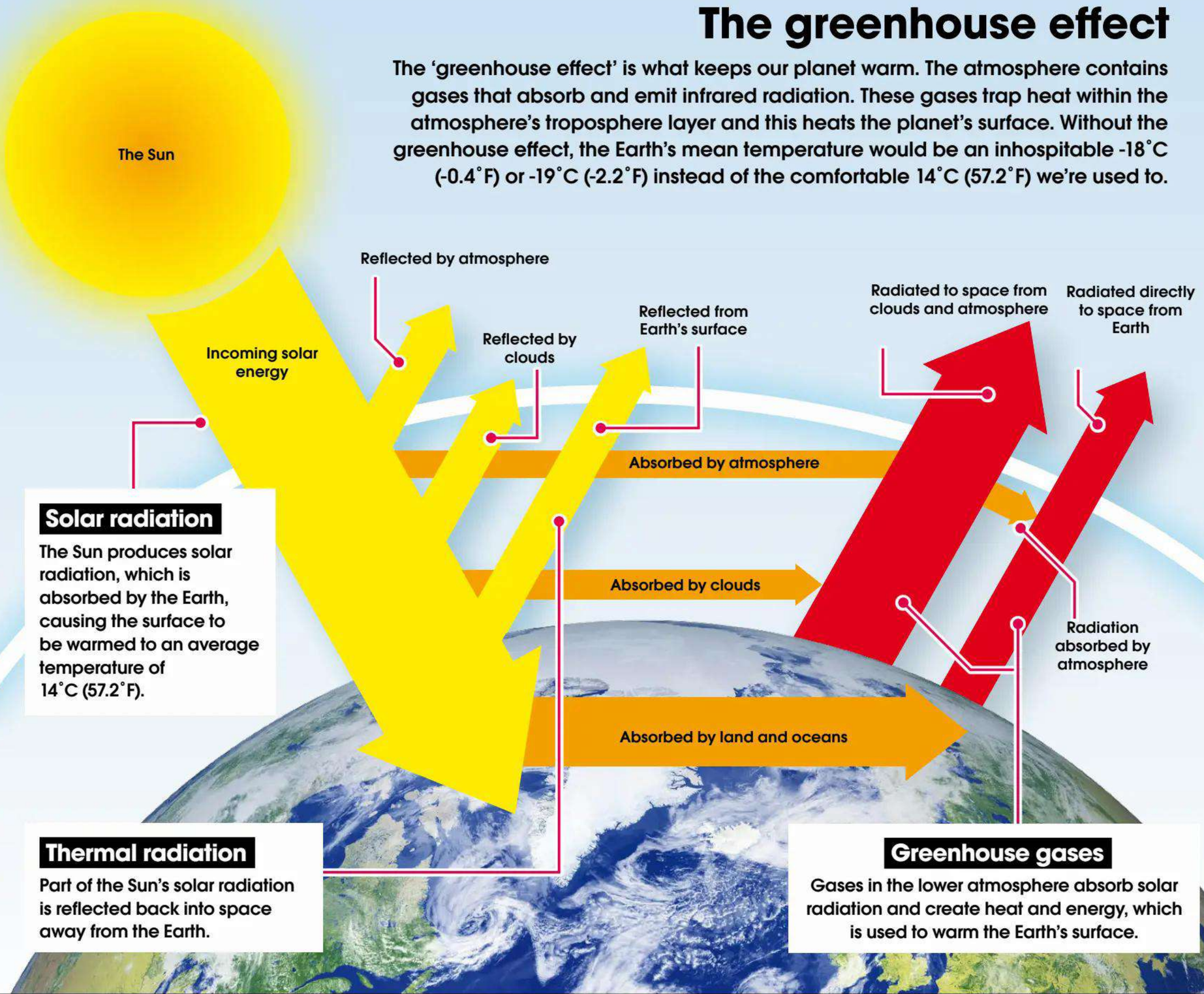
Rife in cities, smog is the result of smoke, fog, and chemical fumes caused when different pollutants combine. Acid rain occurs when a pollutant, such as sulfuric acid combines with droplets of water in the precipitation and becomes acidified.



© NASA

The greenhouse effect

The 'greenhouse effect' is what keeps our planet warm. The atmosphere contains gases that absorb and emit infrared radiation. These gases trap heat within the atmosphere's troposphere layer and this heats the planet's surface. Without the greenhouse effect, the Earth's mean temperature would be an inhospitable -18˚C (-0.4˚F) or -19˚C (-2.2˚F) instead of the comfortable 14˚C (57.2˚F) we're used to.

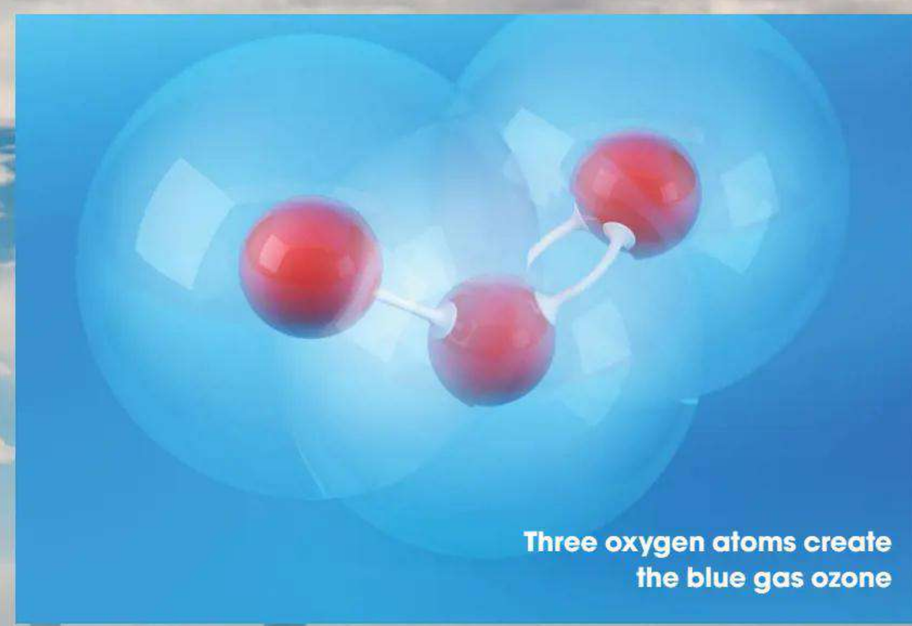


Solar radiation
The Sun produces solar radiation, which is absorbed by the Earth, causing the surface to be warmed to an average temperature of 14˚C (57.2˚F).

Thermal radiation
Part of the Sun's solar radiation is reflected back into space away from the Earth.

Greenhouse gases
Gases in the lower atmosphere absorb solar radiation and create heat and energy, which is used to warm the Earth's surface.

Ozone can be found in the troposphere in the form of smog



Three oxygen atoms create the blue gas ozone

The ozone layer explained

Learn about the layer of gas that surrounds and protects our planet

Ozone is a pale-blue gas composed of three bonded oxygen atoms. It occurs naturally high up in Earth's atmosphere, where it protects the surface from harmful ultraviolet rays – unless dissipated by natural or human phenomena. It's also considered a pollutant, with adverse effects for humans and other creatures when present closer to the ground. Ozone is a relatively unstable substance and can be destroyed by molecules containing nitrogen, hydrogen, chlorine or bromine, which rip ozone's third oxygen atom away from its two partners. Starting in the 1950s, scientists began measuring ozone concentrations above Antarctica, giving them the first hints that there was a problem with the ozone layer.

By the 1980s, researchers were able to map a yearly hole that opened in the ozone layer over Antarctica in the spring, though nobody knew its cause. In 1987, aircraft observations provided unassailable evidence that the ozone hole was being created by human-made pollutants called chlorofluorocarbons (CFCs).

Chlorine and bromine, which are present in chlorofluorocarbons and related compounds, are highly destructive to ozone. A single chlorine atom can rupture more than 100,000 ozone molecules before it leaves the stratosphere. CFCs come from industrial processes like refrigeration and are used in fire suppression and foam insulation, among other applications.

Did you know?
The ozone layer is 16-40km (10-25mi) above Earth's surface.

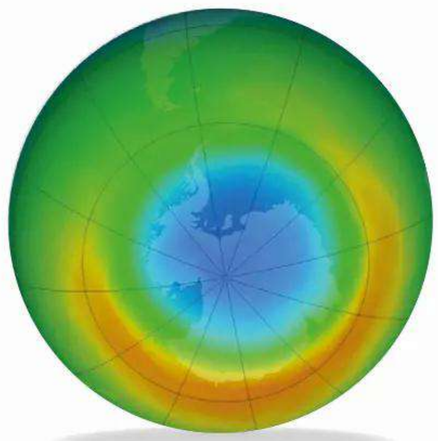
Scientists were able to find that ozone depletion wasn't just occurring over the South Pole, but also in areas over North America, Europe and Asia and much of Africa, Australia and South America. In 1987, countries around the world signed the Montreal Protocol on Substances that Deplete the Ozone Layer, an international document committing signatories to addressing the ozone hole. People have been trying to phase out CFCs and other harmful industrial pollutants ever since.

Polluting the Earth's surface

When ozone is present down near the ground, it can be harmful. Such ozone, also called smog, is created from oxides of nitrogen (NOx) – emitted by cars, power plants, industrial boilers, refineries and chemical plants – combining with other organic molecules in the atmosphere. Breathing in ozone can cause chest pain, throat irritation, coughing and damage to lung tissue. It's most dangerous to children and the elderly and those with pulmonary issues like asthma, emphysema and bronchitis. It is also harmful to vegetation and affects forests, parks and wilderness areas. Ground-level ozone can be reduced by limiting pollutants from cars and factories.

A growing problem

How the ozone hole has shifted over time



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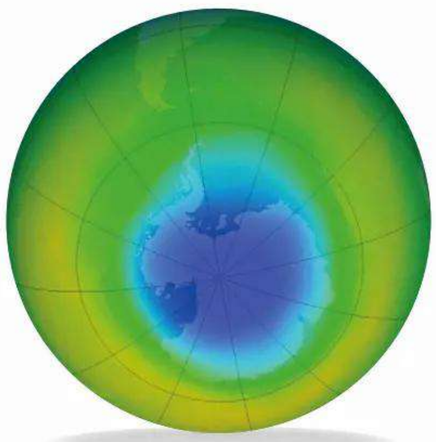

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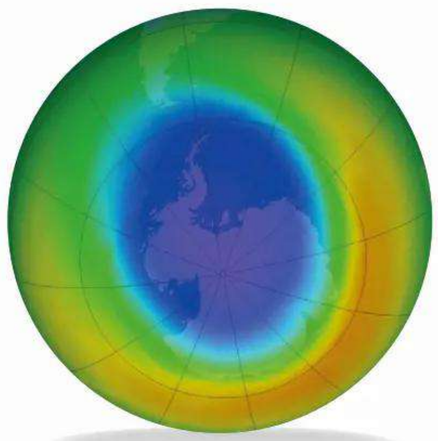


1991

The hole over Antarctica

The ozone layer is much thinner at the poles

Did you know?
In 2021, the hole in the ozone layer was roughly the size of North America.

Seasonal changes
The ozone hole usually appears in August and is recovered by November, when warmer weather prevents damage.

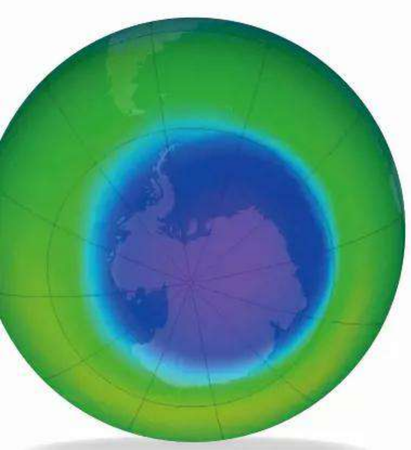
Average thickness
The average thickness of the ozone layer is 300 Dobson units, equating to 3mm (0.12in).

Widening gap
In 2021 the ozone hole was measured at 28.7M km² (11.1M mi²).

Created by cold
The ozone hole occurs over Antarctica because low temperatures are needed to form polar stratospheric clouds – those that form in the stratosphere.

220 Dobson units
Areas of the ozone layer that are less than 220 Dobson units are considered to be holes.

TOTAL OZONE (Dobson units)
110 220 330 440 550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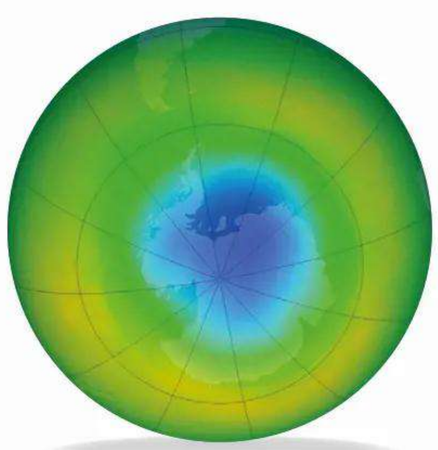
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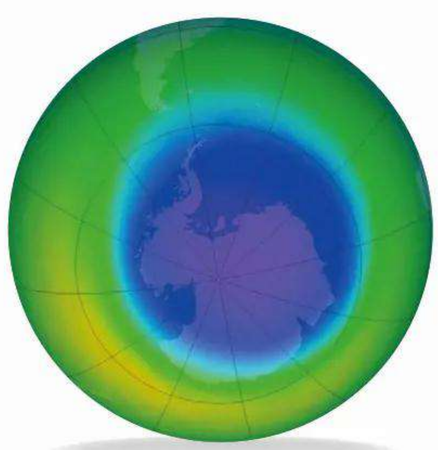
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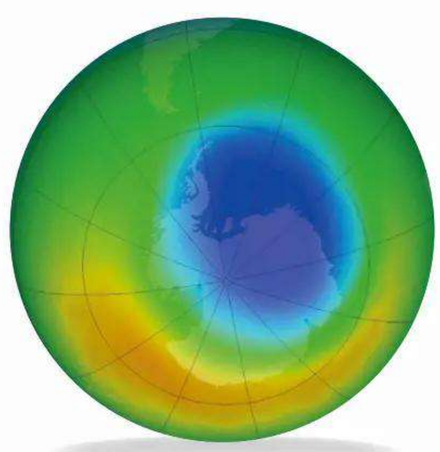
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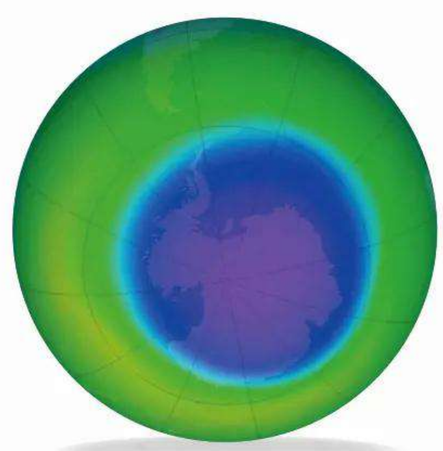

2020

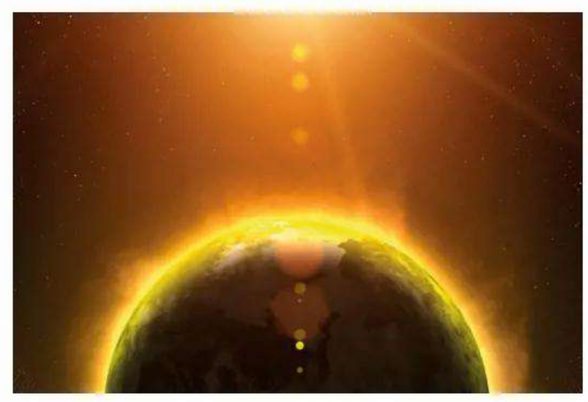
© Getty / Alamy / AR by Adrian Mann

Oxygen vs ozone

Molecular oxygen (O2) is the normal oxygen that we breathe, present throughout the atmosphere. It can be split apart by the Sun's rays into two single oxygen atoms, and one of these can then recombine with an O2 molecule to form O3 – ozone.

The gas has a distinctive and sharp odour, reminiscent of chlorine, and can sometimes be smelled after a thunderstorm, when lightning zaps oxygen molecules apart. This property is what gives ozone its name, after the Greek word ozein, meaning 'to smell'.

The vast majority of ozone sits in the stratosphere. Ozone makes up roughly 0.00006 per cent of the atmosphere, and peak concentrations of it are present around 32km (20mi) above the surface in an area known as the ozone layer. At that height, ozone absorbs intense ultraviolet radiation streaming in from the Sun.



Without the ozone layer, the ground on Earth would be sterilised and life as we know it wouldn't be possible

The water cycle

Rain falling today has spent billions of years travelling between Earth's clouds, oceans and ice

The water – or hydrological – cycle is the Earth's water recycling system. Since water rarely escapes the planet or arrives from space, the water cycle keeps rivers relentlessly flowing into the oceans and the atmosphere supplied with clouds and rain. Without it, life simply couldn't exist.

The water cycle circulates water between the oceans and atmosphere, sometimes via the land. When ocean water is heated, it turns into water vapour, which rises into the atmosphere and is carried by winds. The vapour cools at some point and forms clouds. Around 78 per cent of the rain, snow and other forms of precipitation falling from these clouds goes straight back into the ocean. The rest falls over the Earth's continents and islands.

Some of this water runs into rivers and lakes and is carried back to the sea. Water also seeps back to the oceans through deep soil and rocks, becoming the Earth's groundwater. Water falling as snow over the polar ice sheets can be buried, sometimes for millions of years, until it reaches the sea via slow-moving glaciers.

Water that stays in shallow soil can be lifted back into the atmosphere when it warms. Alternatively, plants may suck up soil water through their roots and return it to the atmosphere through their leaves. When animals eat plants, they take the water into their bodies and expel it into the air in their breath.

Humans alter the water cycle on land by building cities and flood controls, and capturing water for drinking, agriculture and industry.

5 top facts

1 Ancient science
People first mentioned the water cycle around 2,000 years ago. One of the oldest Hindu scriptures, the Chandogya Upanishad, said "rivers... lead from sea to sea".

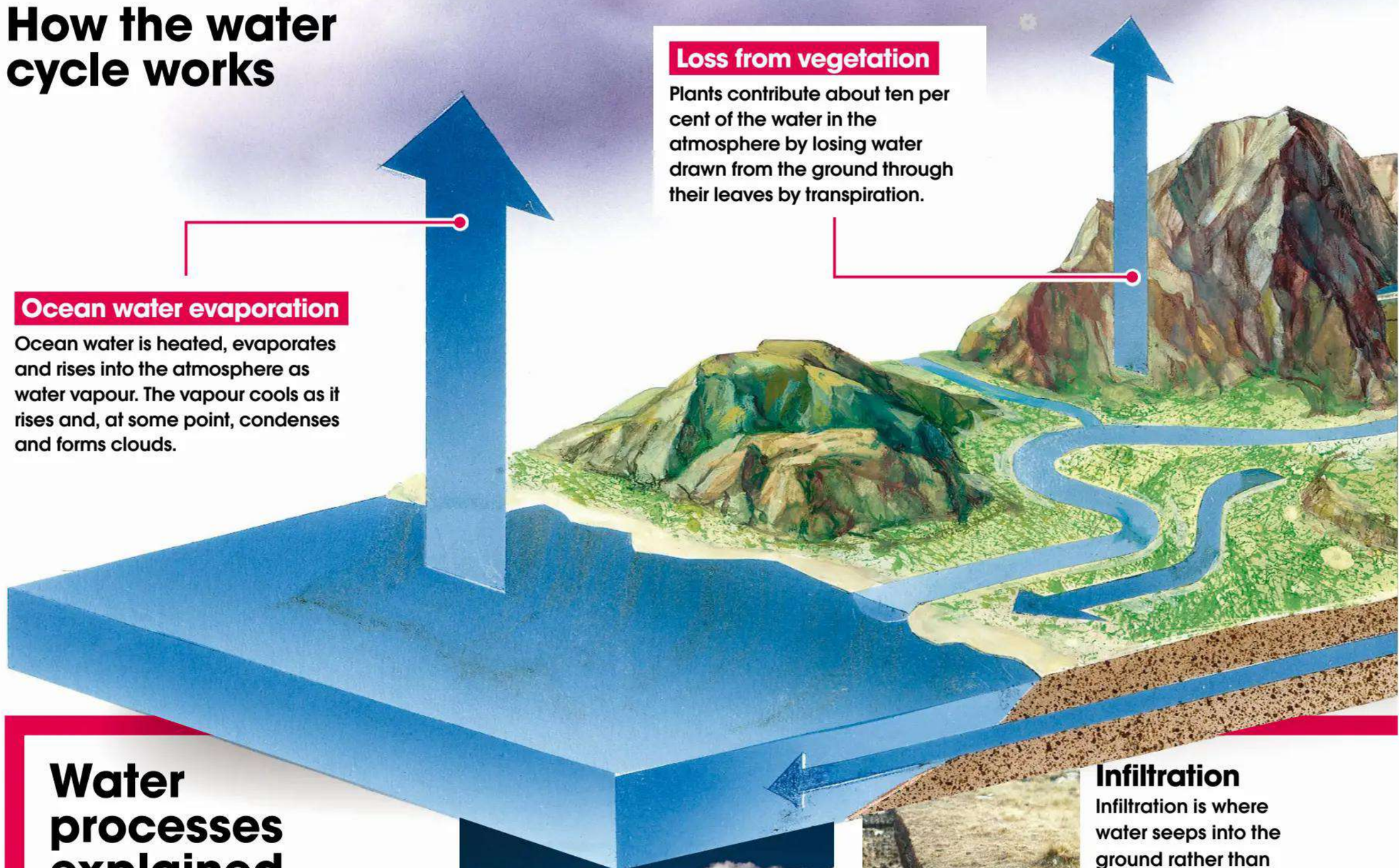
2 Drop to drink
Most people get water from rivers and lakes, which form just 0.014 per cent of the world's water. The rest is mainly in the oceans (96.5 per cent), ice or underground.

3 Olympic deluge
A small thunderstorm can produce, on average, 2,000 tons of rain in just 30 minutes. That's enough to fill an Olympic-sized swimming pool.

4 Earliest water
Liquid water may have existed on Earth for 4.4 billion years. The water in your glass is almost as old as our planet and significantly older than the dinosaurs.

5 Slow moving
Water can spend more than 10,000 years locked up in deep groundwater or the polar ice sheets, but just a few days in the atmosphere.

How the water cycle works



Ocean water evaporation
Ocean water is heated, evaporates and rises into the atmosphere as water vapour. The vapour cools as it rises and, at some point, condenses and forms clouds.

Loss from vegetation
Plants contribute about ten per cent of the water in the atmosphere by losing water drawn from the ground through their leaves by transpiration.

Water processes explained

Condensation

When you breathe on a cold window and it fogs up, you're seeing condensation in action. It's the process by which water vapour in the air turns back into liquid water when it cools down. Atmospheric water vapour condenses on salt, smoke and dust particles to form clouds.

Infiltration

Infiltration is where water seeps into the ground rather than running across it. Once in the ground, the water stays in shallow soil layers or moves deeper to form groundwater. Dry, loose soils on flat ground will absorb more water than steeply sloping hard surfaces or already wet soil.

Water vapour transport

Around eight per cent of the water evaporated from the oceans is carried over the land by winds circulating through the atmosphere.

Rainfall

Rain runs off into rivers or infiltrates into the ground where it is taken up by plants or moves into groundwater.

Did you know?

The Sun powers the water cycle, moving around 14M t (15.5M tn) of water through the atmosphere every second.

Snowfall

Snow melts immediately or when the weather warms, but if it falls on glaciers or ice sheets, it can be locked up for hundreds or even millions of years.

Surface water evaporation

Around 14 per cent of evaporation occurs over land from lakes, rivers, ice and the ground. Ice also turns straight into water vapour without melting, a process called sublimation.

Groundwater

Water infiltrating into the soil can seep into the ground where it flows towards streams and the ocean, or enters deep underground stores called aquifers.

The River Indus is now some 30km (18.6mi) wide in places

When the water cycle lets us down

Floods affect tens of thousands of people each year. Examples of this were the devastating monsoon floodings across Pakistan in 2010 and 2022. The floods, which displaced over 6 million and 7.9 million people respectively, were the result of the heaviest monsoon rains in the area for generations. In both cases, the River Indus burst its banks, sweeping away entire communities. While it's normal for Pakistan to receive half its annual rainfall (250-500mm/10-20in) during the monsoon months of July and August 2022, the country received a record-breaking 450mm (18in) of rain. Possible reasons for the unusually heavy rains, include changes to upper atmosphere airflow, active monsoon systems, and La Niña (El Niño in reverse).

Serious floods, like those seen in Pakistan in 2010 and 2022, can cause catastrophic destruction

Runoff

Water flowing down tarmac roads into curb-side drains after a storm is an example of the process of runoff. Rain that doesn't evaporate or infiltrate into soil or rock also flows down small channels as runoff. The channels merge into streams that, eventually, join rivers flowing downhill to the sea.

Evaporation

Wet clothes hung outside dry by evaporation, the process by which liquid water turns into vapour when heat energy breaks bonds between its water molecules. Soaking a T-shirt keeps you cool on a hot day because since evaporation uses up heat energy from the air, it reduces nearby temperatures.

Precipitation

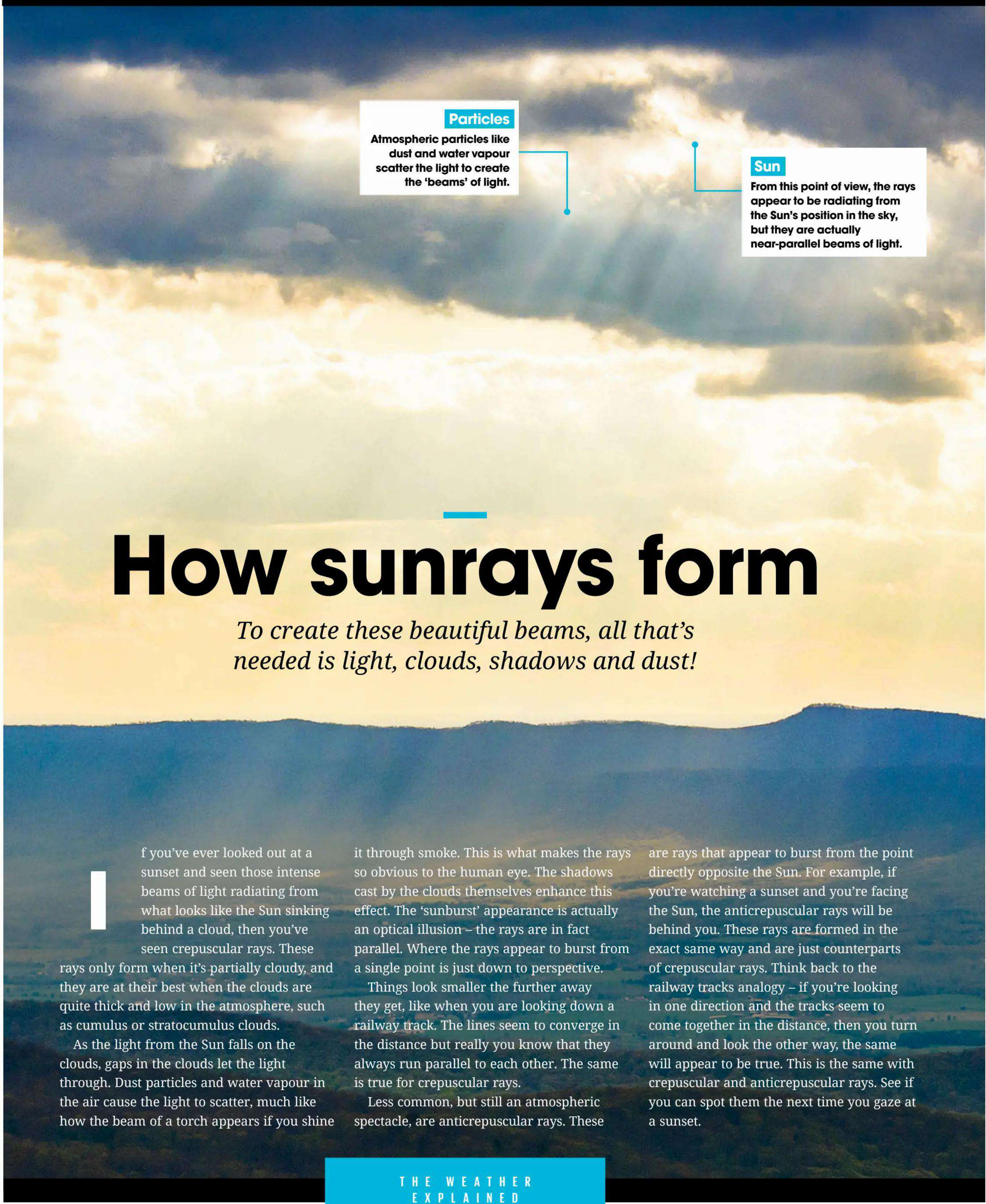
Precipitation is a catch-all term for water falling from clouds to the earth. It covers rain, snow, hail and so on. Precipitation happens when water vapour condenses on airborne particles as droplets. These grow bigger by, for example, collisions until they become so heavy they fall to the ground.

Transpiration

Plants – like humans – breathe out water vapour, a process called transpiration. During transpiration, water drawn into a plant's roots is carried to the leaves where it evaporates. How much plants transpire varies depending on air temperature, humidity and incoming sunlight. Higher temperatures and stronger sunlight mean more transpiration.

© Dr Philip Bethge, 1999 © DK Images

The weather explained



How sunrays form

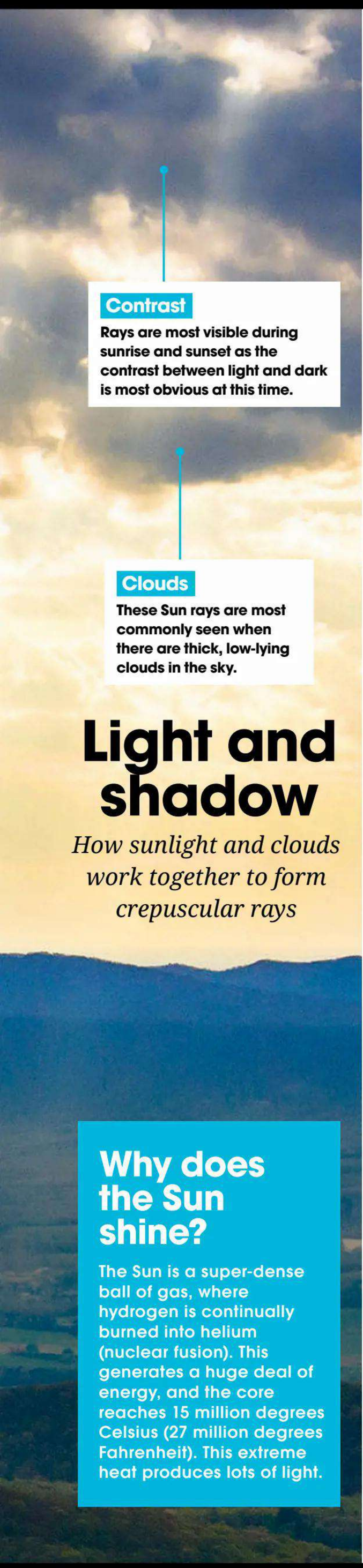
To create these beautiful beams, all that's needed is light, clouds, shadows and dust!

If you've ever looked out at a sunset and seen those intense beams of light radiating from what looks like the Sun sinking behind a cloud, then you've seen crepuscular rays. These rays only form when it's partially cloudy, and they are at their best when the clouds are quite thick and low in the atmosphere, such as cumulus or stratocumulus clouds.

As the light from the Sun falls on the clouds, gaps in the clouds let the light through. Dust particles and water vapour in the air cause the light to scatter, much like how the beam of a torch appears if you shine it through smoke. This is what makes the rays so obvious to the human eye. The shadows cast by the clouds themselves enhance this effect. The 'sunburst' appearance is actually an optical illusion – the rays are in fact parallel. Where the rays appear to burst from a single point is just down to perspective.

Things look smaller the further away they get, like when you are looking down a railway track. The lines seem to converge in the distance but really you know that they always run parallel to each other. The same is true for crepuscular rays.

Less common, but still an atmospheric spectacle, are anticrepuscular rays. These are rays that appear to burst from the point directly opposite the Sun. For example, if you're watching a sunset and you're facing the Sun, the anticrepuscular rays will be behind you. These rays are formed in the exact same way and are just counterparts of crepuscular rays. Think back to the railway tracks analogy – if you're looking in one direction and the tracks seem to come together in the distance, then you turn around and look the other way, the same will appear to be true. This is the same with crepuscular and anticrepuscular rays. See if you can spot them the next time you gaze at a sunset.



Contrast
Rays are most visible during sunrise and sunset as the contrast between light and dark is most obvious at this time.

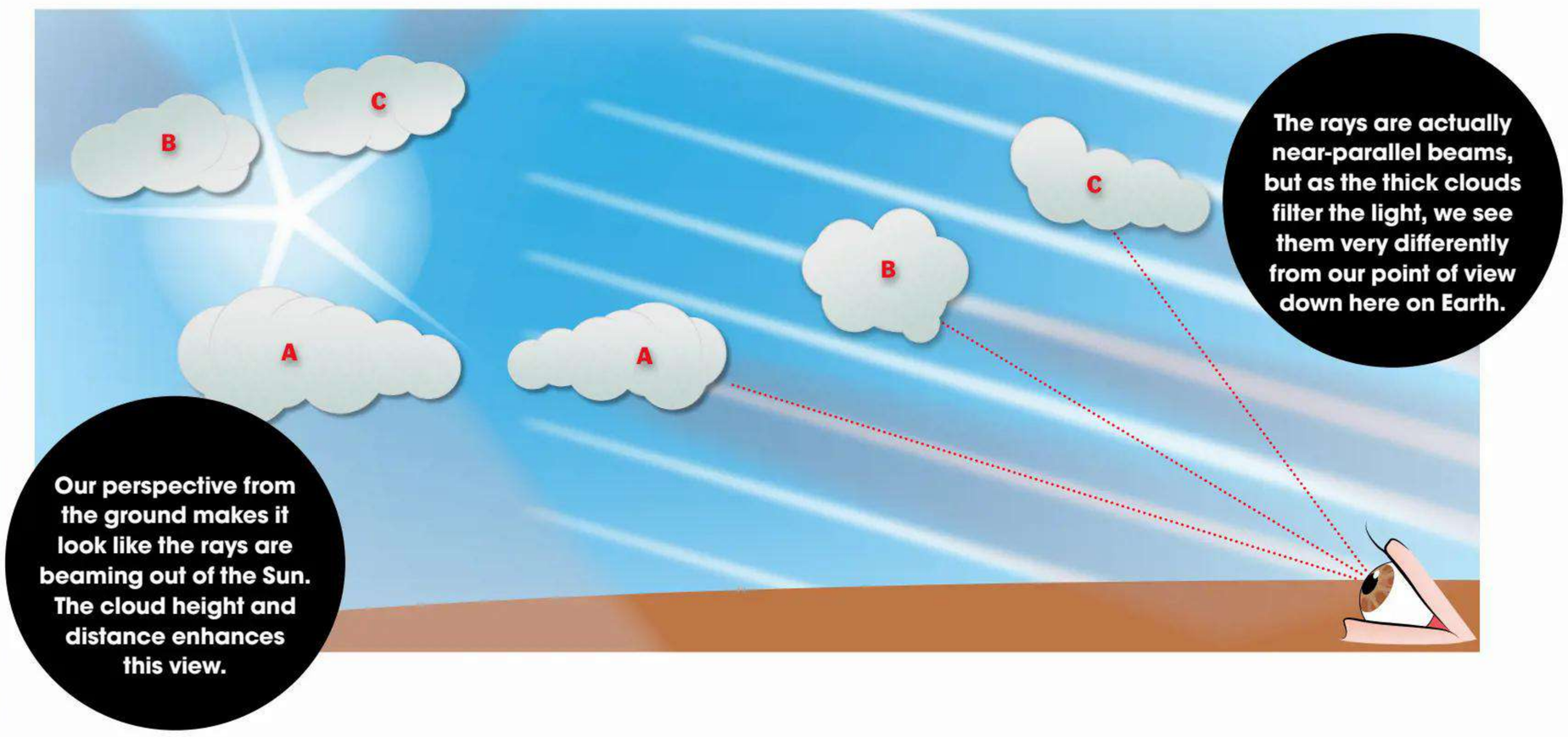
Clouds
These Sun rays are most commonly seen when there are thick, low-lying clouds in the sky.

Light and shadow

How sunlight and clouds work together to form crepuscular rays

Why does the Sun shine?

The Sun is a super-dense ball of gas, where hydrogen is continually burned into helium (nuclear fusion). This generates a huge deal of energy, and the core reaches 15 million degrees Celsius (27 million degrees Fahrenheit). This extreme heat produces lots of light.

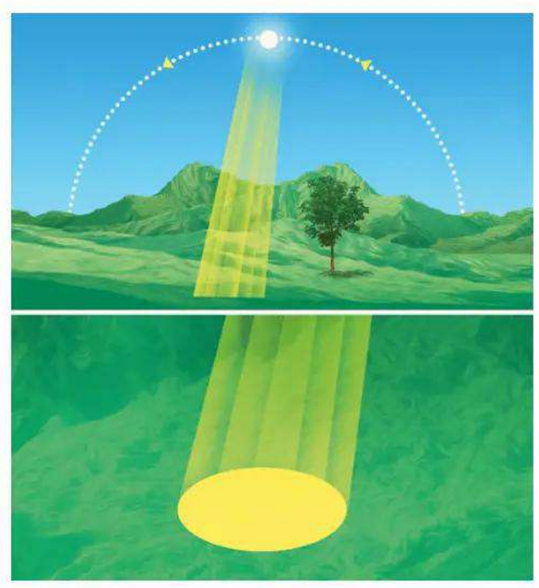


The rays are actually near-parallel beams, but as the thick clouds filter the light, we see them very differently from our point of view down here on Earth.

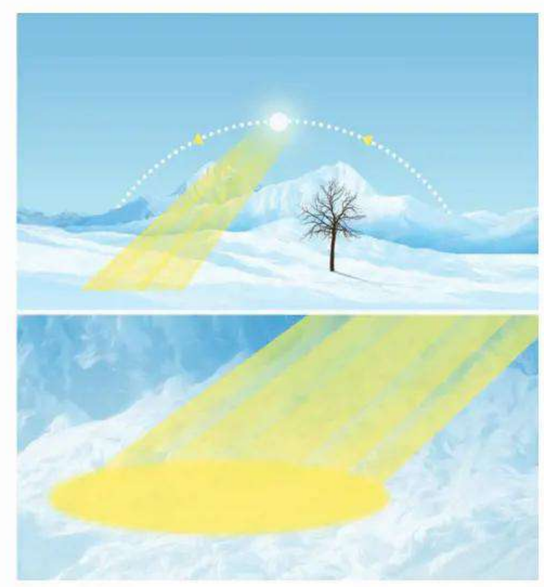
Our perspective from the ground makes it look like the rays are beaming out of the Sun. The cloud height and distance enhances this view.

How does the Sun cause the seasons?

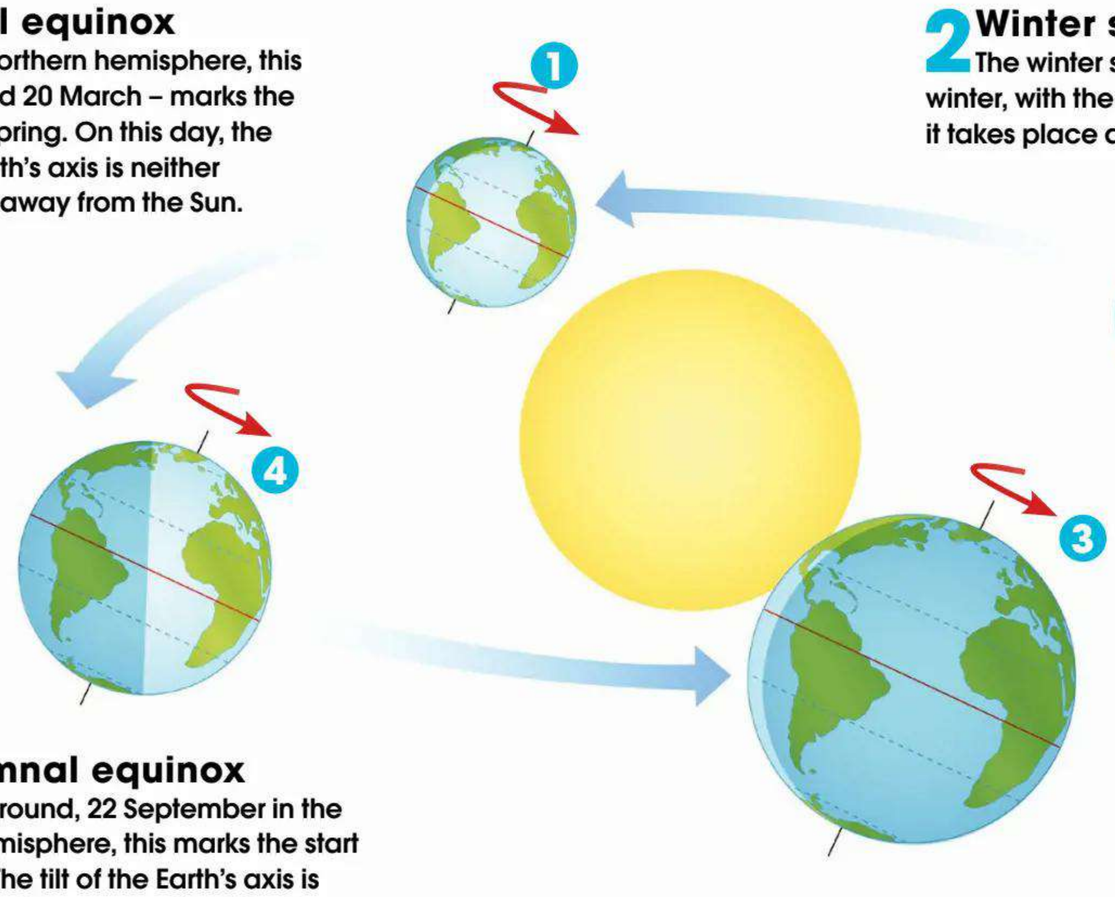
Seasons are caused by the Earth's revolution around the Sun, as well as the tilt of the Earth on its axis. The hemisphere receiving the most direct sunlight experiences spring and summer, while the other experiences autumn and winter. During the warmer months, the Sun is higher in the sky, stays above the horizon for longer, and its rays are more direct. During the cooler half, the Sun's rays aren't as strong and it's lower in the sky. The tilt causes these dramatic differences, so while those in the northern hemisphere are wrapping up for snow, those in the southern hemisphere may be sunbathing on the beach.



SUMMER
The Sun is at its highest point in the sky and takes up more of the horizon. Its rays are more direct.



WINTER
The Sun is at its lowest point in the sky and there is less daylight. The rays are also more diffuse.



1 Vernal equinox
For the northern hemisphere, this day – around 20 March – marks the first day of spring. On this day, the tilt of the Earth's axis is neither towards nor away from the Sun.

2 Winter solstice
The winter solstice marks the beginning of winter, with the Sun at its lowest point in the sky; it takes place around 20 December each year.

3 Summer solstice
During the summer solstice, around 20 June, the Sun is at its highest, or northernmost, point in the sky.

4 Autumnal equinox
On, or around, 22 September in the northern hemisphere, this marks the start of autumn. The tilt of the Earth's axis is neither towards nor away from the Sun.

© Illustration by Alex Phoenix; Thinkstock

Why is the sky blue?

Ancient philosophers puzzled over why the sky is blue – now we know it's all down to something called Rayleigh scattering

Blue skies are such a familiar sight, it's easy to overlook the science behind them.

Everyone loves a blue sky, but why does it take on that colour when it isn't obscured by clouds? The answer lies in the physics of what happens when sunlight passes through the atmosphere. The light rays are scattered in all directions as they hit air molecules, and light at the blue end of the spectrum is scattered more strongly than other colours. That's why the sky usually appears blue when we look in any direction away from the Sun itself.

Above Earth's atmosphere, in space the sky looks black even in sunlight. That's one of the most striking phenomena experienced by travellers on Blue Origin's suborbital flights: "To see the blue colour whip by you, and now you're staring into blackness," as William Shatner put it after his flight. This blackness is easy enough to understand. Unless you're looking directly at the Sun, there's no reason for the sky to be illuminated at all. The real puzzle is why it's illuminated down here on the surface of the planet – a long-standing mystery that wasn't fully explained until the end of the 19th century.

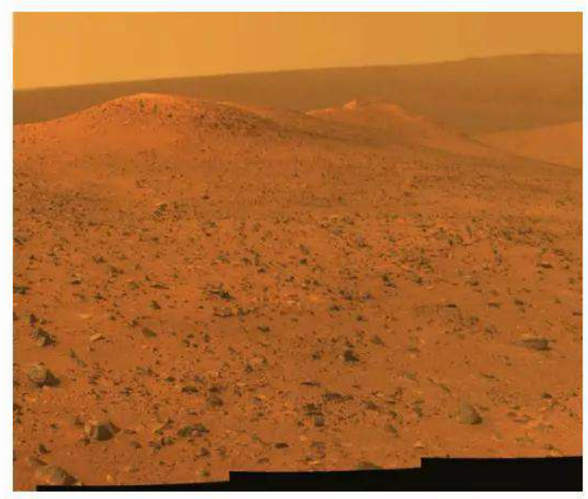
The key lies in an effect known as Rayleigh scattering, named after its discoverer Lord Rayleigh. This refers to the way that light bounces off small particles – up to about one-tenth the wavelength of the light itself – which includes the molecules making up Earth's atmosphere. Rayleigh showed that longer wavelengths, corresponding to the red end of the spectrum, aren't scattered as strongly as short wavelengths like blue and violet. Of those two colours it's the blue that dominates, partly because our eyes are more sensitive to it and also because the Sun emits less violet light to begin with.

Did you know?
Blue light has a wavelength of 450 to 495 nanometres.

Even looking to the Sun, the sky is black at the altitude of the International Space Station

The sky on Mars

Since the first NASA landers arrived on Mars, it's been known that the sky on that planet has a predominantly red tint. This is also due to atmospheric scattering, but not of the Rayleigh kind. Rayleigh scattering is produced by air molecules, which are smaller than the wavelength of light, and these are less important in the thin atmosphere of Mars than wind-blown dust. The latter is made up of much larger particles, and for these a different scattering mechanism comes into play, resulting in the distinctive reddish-orange colour of the Martian sky.



This photograph from Opportunity shows the characteristic orange-red colour of the Martian sky

Blue sky physics

The theory of Rayleigh scattering explains why the sky is blue

Sunlight in space
Light emitted by the Sun contains a mixture of all wavelengths, so it looks white.

Rayleigh scattering
As sunlight passes through the atmosphere, it's scattered in all directions by the air molecules.

Shorter wavelengths
Colours at the short end of the spectrum are scattered the most, which is why the sky looks blue.

Longer wavelengths
Other colours are scattered to a smaller degree, so the Sun itself tends to look yellowish.

5 Facts about blue skies

The sea is also blue
The sea's blue colour is unrelated to the blue sky. Water molecules absorb red light, so a large body of water only reflects the bluer portions of light illuminating it.

Clouds are white
Unlike air molecules, the water droplets in clouds are much larger than the wavelength of light, so they reflect all colours equally.

Fog-light fallacy
The water droplets in fog also reflect all wavelengths equally, so it's a misconception that yellow fog lights penetrate through it better than white ones.

A record-breaking problem
The question of the sky's blue colour, dating back at least 2,300 years, was the longest standing unanswered question in physics until Lord Rayleigh finally solved it in the 19th century.

A prolific scientist
As well as Rayleigh scattering, Lord Rayleigh has several other scientific principles named after him, including Rayleigh distribution, Rayleigh-Jeans law and Rayleigh-Schrödinger perturbation theory.

Why are sunsets red?

The sky isn't always blue. When the Sun is low in the sky, at sunrise or sunset, it can take on a red hue. This is explained by the same physics – Rayleigh scattering – as the blueness of the sky at other times. When we look towards the Sun at sunset, we're seeing light that has travelled further through the atmosphere than when the Sun is high in the sky. Most of the shorter wavelengths have been scattered away, and we just see what's left. The dramatic phenomenon of a blood Moon, when the Moon turns red during a lunar eclipse, is also caused by sunlight passing through a large thickness of Earth's atmosphere. It happens when Earth blocks direct sunlight from reaching the Moon – its only source of illumination is light that has already travelled all the way through Earth's atmosphere.

A deep-red sunset seen over Tower Bridge in London

© Getty / NASA

What is humidity?

Discover the cause of uncomfortable, muggy weather that leaves you sweating

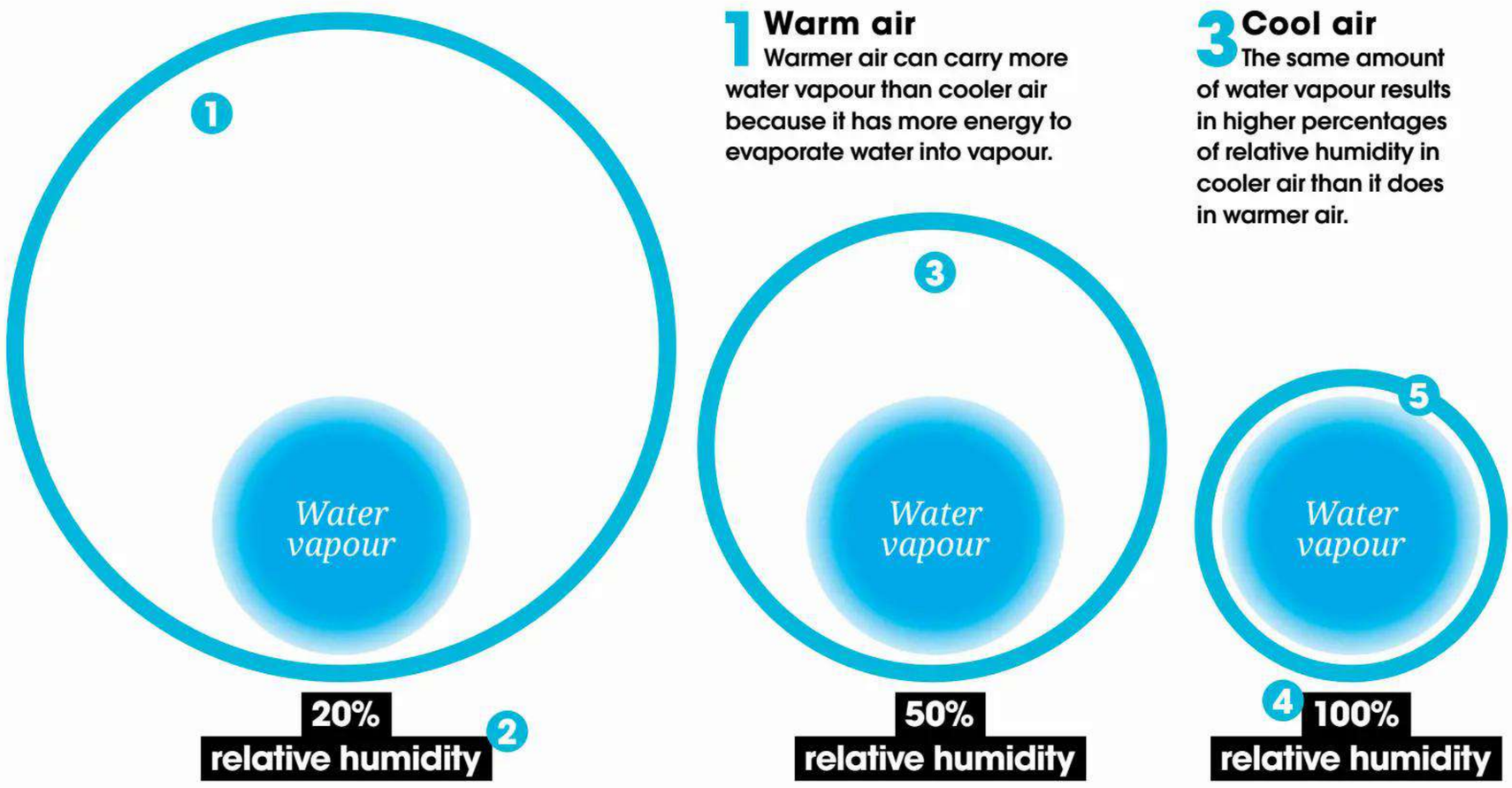
Dew can form on the ground when the surrounding air becomes saturated with water vapour

When it's humid, your sweat does not evaporate so easily

The air around you contains water in the form of a gas called water vapour, and the amount of vapour it contains is known as its humidity. If you have ever visited somewhere with a tropical climate then you may have experienced humid, muggy air, which can often leave you feeling uncomfortably hot. This is because the air around you is saturated, and cannot hold any more water vapour, so the sweat from your skin cannot evaporate to cool you down. Humidity can actually also affect you in cool climates, as the water vapour in the air conducts the cold temperature onto your skin, making you feel colder.

Calculating humidity

How does air temperature affect the relative humidity?



1 Warm air
Warmer air can carry more water vapour than cooler air because it has more energy to evaporate water into vapour.

3 Cool air
The same amount of water vapour results in higher percentages of relative humidity in cooler air than it does in warmer air.

"The air is saturated, and can't hold any more water vapour"

2 Relative humidity
Relative humidity measures how much water vapour is in the air compared to the maximum that there could be at that specific temperature.

4 Dew point
When the air cannot hold any more water vapour, it will start to condense as dew.

5 Saturation
When the air is carrying as much water vapour as it can hold, it is described as 'saturated'.

© Thinkstock

"Gatherings of condensed water vapour are called clouds, and this is where rain comes from"

What's the difference between rain, sleet and snow?

When it comes to precipitation, it's all about temperature. When the air is sufficiently saturated, water vapour begins to form clouds around ice, salt or other cloud seeds. If saturation continues, water droplets grow and merge until they become heavy enough to fall as rain. Snow forms when the air is cold enough to freeze supercooled water droplets – lower than 0 degrees Celsius (32 degrees Fahrenheit) – then falls. Sleet is somewhere in between: it starts as snow but passes through a layer of warmer air before hitting the ground, resulting in some snow melting.

Why, and how, does it rain?

Most people associate the rain with gloomy weather, but it is very important for the maintenance of our ecosystem

Rain is defined as liquid precipitation. It is formed high above the ground in clouds by water vapour coming together into large droplets that become too heavy for the air to support. Gatherings of condensed water vapour are called clouds, and this is where rain comes from. Although a large amount of water is held in each cloud, rain does not fall all at once from the cloud because the water droplets grow at different speeds, with the fastest growing droplets becoming heavier quicker and falling first, the slower growing ones falling after.

Although scientists are not sure if there is water on other planets, the phenomenon of rain has occasionally been recorded. This rain involves other liquids, such as methane which falls on Titan, Saturn's moon, and sulphuric acid which falls on Venus.

1 Water evaporates

Water on the Earth's surface is heated by the Sun, and small water droplets evaporate into the air.

2 Water vapour travels

The heat from the Sun pulls these water vapour droplets upwards into the atmosphere.

3 Clouds form

When the water vapour droplets reach a certain level, condensation starts to occur, forming clouds. This is due either to an increase in humidity or a drop in temperature in the atmosphere.

4 Rain forms

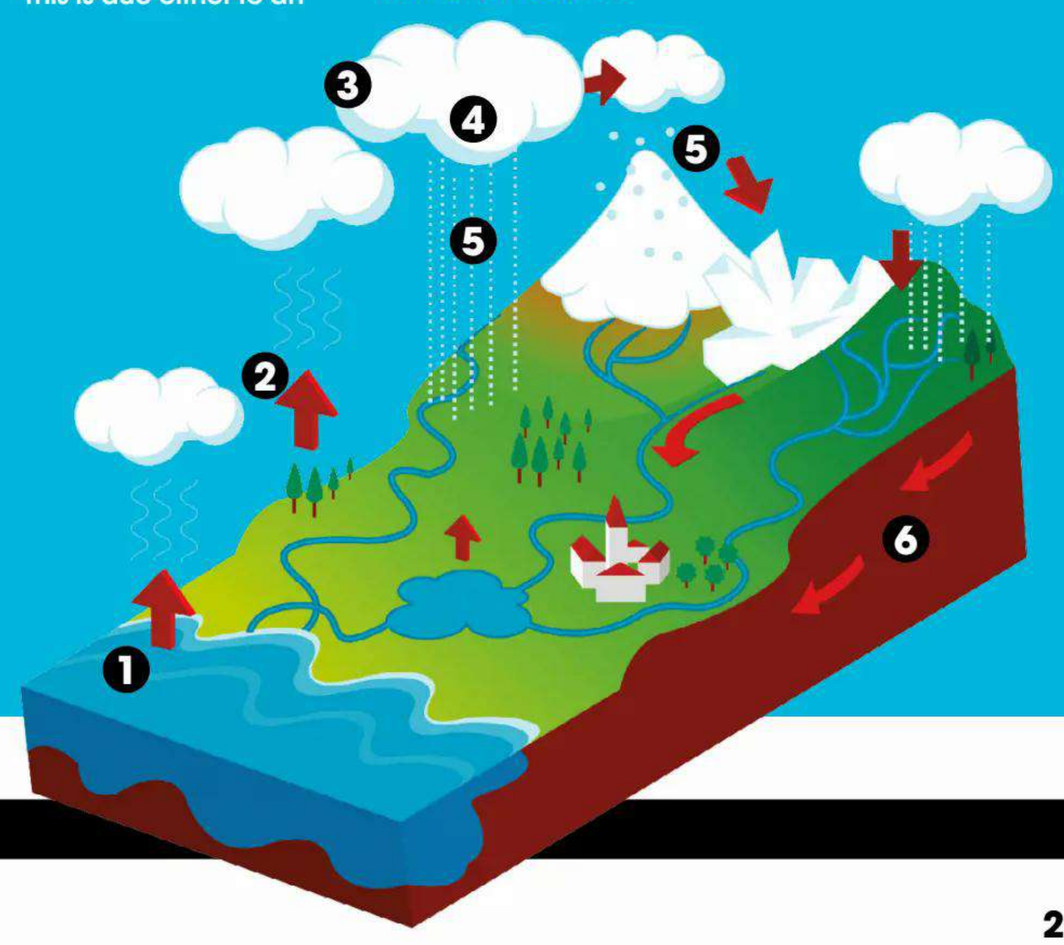
As more water vapour droplets gather within the cloud, they start to merge and become larger. Eventually they will become too heavy to be held in the atmosphere and gravity will start to pull them back towards Earth.

5 Rain falls

This water falling back to Earth is called rain. Sometimes it will not make it back to Earth, due to the air not being humid enough, and in this case, water evaporates back into the atmosphere. If the temperature of the air is lower than normal, the water will freeze and fall as snow or hail.

6 Water returns to the Earth

If the water that falls is not caught by plants or animals, water hits the ground and, if not evaporated from the land, it will start to move back towards rivers, streams and the sea – where the process begins again.



© Getty

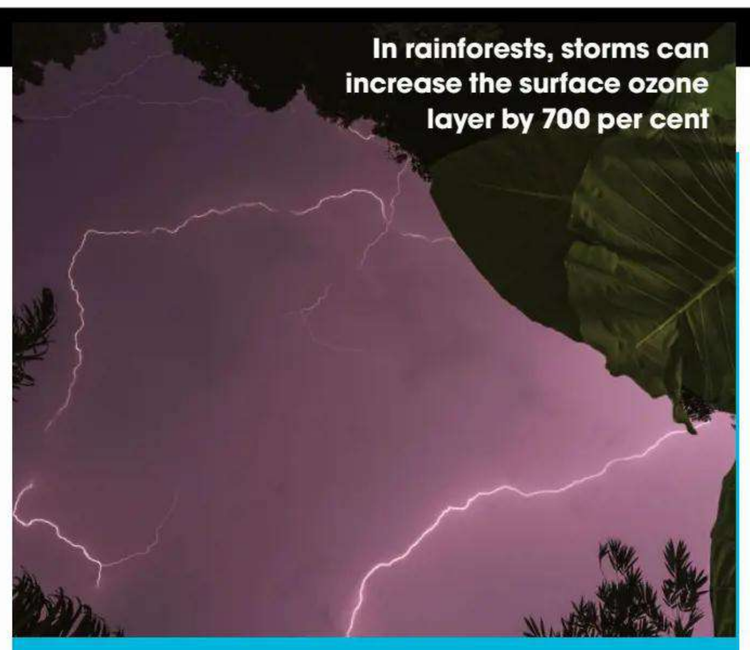
What is the smell of rain?

After rainfall, this distinctive aroma is released from the soil

Despite being seen as an unwelcome form of weather by many, rain is an essential event for sustaining life on Earth. Communities throughout history have always welcomed rainfall as an aid to their growing crops – and scientists think it's for this reason that so many still enjoy the smell that follows the rain. This is called petrichor.

The raindrops themselves aren't responsible for the scent that fills the air after it starts to rain. Rather, the water droplets cause various fragrant compounds to be released from the soil. As raindrops scatter over dry earth, the water traps tiny bubbles of air at the ground's surface. These droplets then splatter, bursting the bubbles from the loose soil and carrying plant oils and other natural chemicals upwards into the air in an aerosol form.

Did you know?
Humans can smell a few molecules of geosmin per trillion air molecules.



In rainforests, storms can increase the surface ozone layer by 700 per cent

Stormy scent

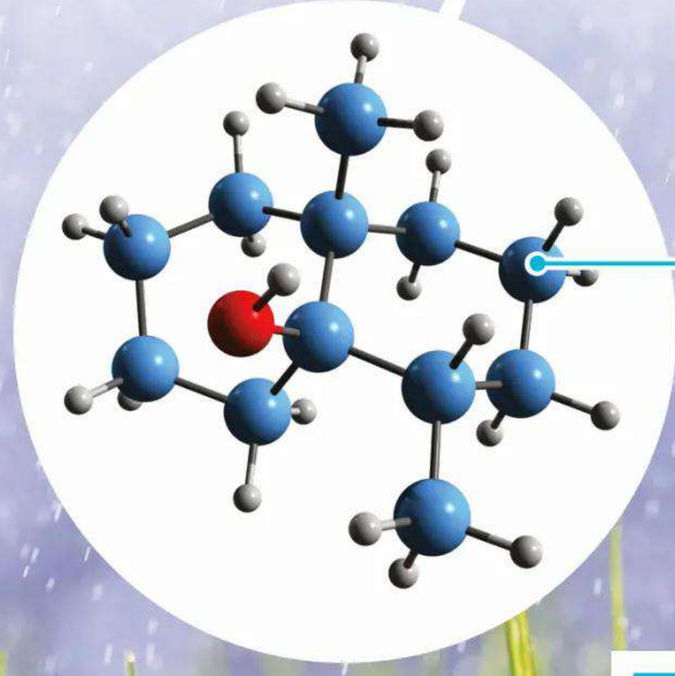
Rain isn't the only weather event that's responsible for natural and distinctive smells. Thunderstorms produce a different scent that's caused by a disturbance in the atmosphere. When lightning strikes through the atmosphere, nitrogen and oxygen molecules split and combine with each other to form nitric oxide and single oxygen atoms. These oxygen atoms then react with oxygen molecules in the air, making ozone (O3). Ozone is a less stable molecule compared to oxygen's elemental form (O2). During a storm, air sinks to form downdrafts and pushes ozone lower into the atmosphere where we can smell it. It has a metallic scent, which makes it possible to identify when rain is soon to fall.

Producing petrichor

Meet the bacteria partly responsible for rain's earthy scent

Bacteria
A specific type of bacteria called actinomyces release spores from the soil. As they do so, the bacteria also produce a compound called geosmin.

Rainfall
When rain falls onto grass, the damp conditions cause bacteria in the soil to release reproductive cells called spores.



Oil odour
When the weather is dry, plants secrete oils. Then, during rainfall, the accumulated oil mixes and bursts into the air to release a stronger earthy scent.

Geosmin
This naturally occurring organic compound (C12H22O) has an earthy smell, called petrichor.

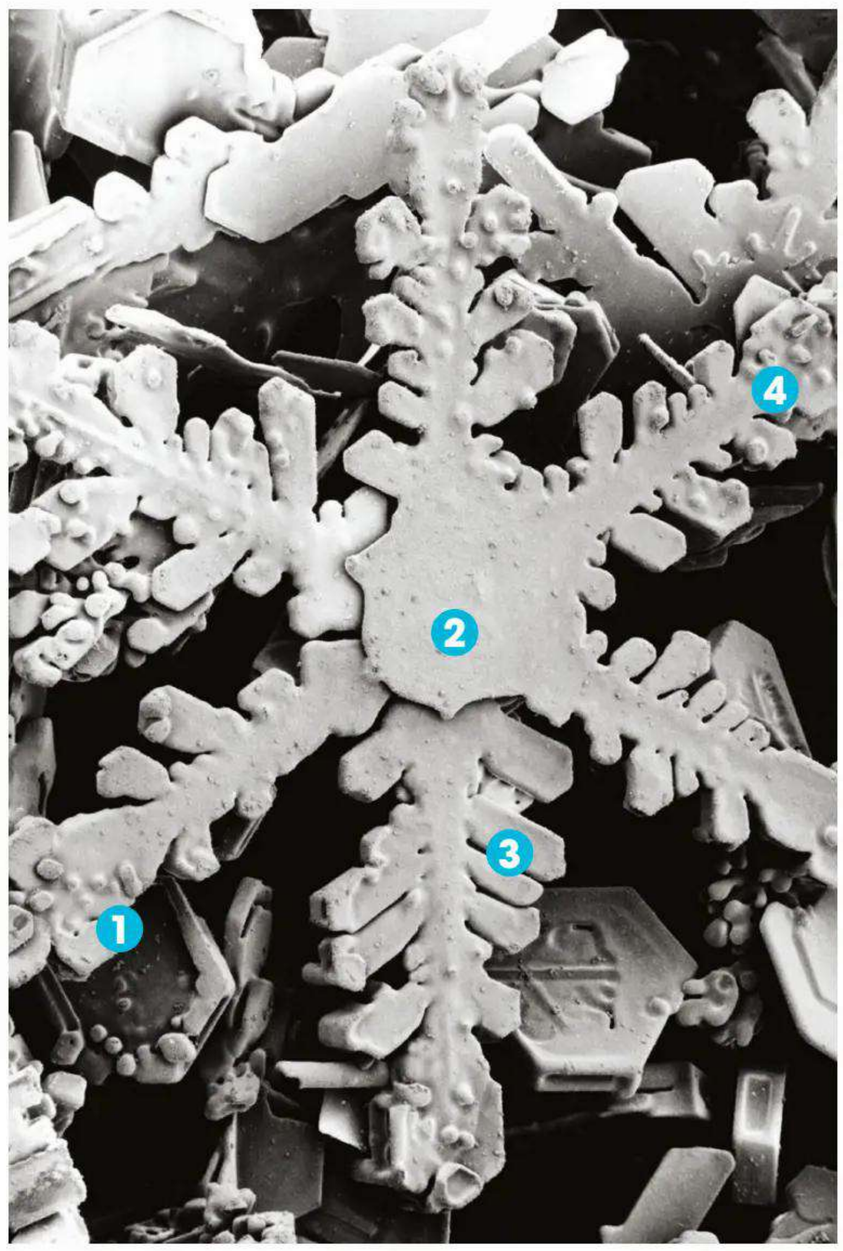
© Alamy / Getty

Why is snow white?

How light changes our perception of snow

To answer this question there are two things which need to be considered – colour theory and refraction. Refraction is the change in direction of light as it goes from one material to another. It's due to a slight change in the speed of the light, and it explains why straws look bent in water. When light enters snow, it refracts. This is because snow is made from lots of ice crystals tightly packed together, the important fact here being that these crystals are translucent – light can pass through, but not in a direct path; it changes direction.

Additive colour mixing tells us that if we combine all of the frequencies of colours we get white light. When light falls on snow it is composed of a mixture of different frequencies which all refract slightly differently as they enter the ice crystals. Eventually, due to refraction, the light leaves the surface of the snow in all directions and hits our eyes. This light is composed of a mixture of frequencies, which our eyes detect as white light.



1 Shape The unique shape of a snowflake is dependent on temperature and moisture.

2 Main facet Water vapour freezes on to a molecule of ice, creating a flat surface called a facet.

3 Main branches Each snowflake develops six branches from the central hexagonal facet.

4 Symmetry Each branch extends outwards at exactly the same rate as all the others.

Snowflakes

How are these beautiful crystals of ice formed?

The formation of a snowflake begins when a microscopic cloud droplet freezes as a tiny ice particle. Water vapour that condenses on its surface causes the ice to develop flat, polished surfaces, known as facets, which continue to grow into a hexagonal prism shape. At each corner of the hexagon shape, new branches extend outwards each at the same rate. All snowflakes have six sides and can be either prism-shaped, plate-shaped or star-shaped.

As the snowflake moves around within the cloud, it encounters a variety of temperatures that change the growth behaviour of each flake, causing the six branches of the crystal to grow in exactly the same way, creating six-way symmetry and a unique flake every time.

The first person to photograph a snowflake was American Wilson Bentley. Bentley took his first snowflake snap in 1885, using a bellows camera and a compound microscope, and went on to assemble a large collection of beautiful snow crystal images.

© Getty / Wiki: Brian0918

How clouds reveal the weather

Shaped by the landscapes they cross, clouds warn us about incoming storms and even form on other planets

The sky is often abundant with clouds. We usually take little notice of them hovering above our heads, but sometimes we fear the weather they may bring. Continuously appearing and fading out of sight, what are these unique shapes that parade across the sky?

Clouds are created when rising air cools down enough to release the water vapour it contains, and the condensation produced in this process makes clouds visible. Cloud masses consist of tiny droplets of liquid, frozen crystals and other suspended particles, such as sea salt, dust and dirt. These particles are known as cloud condensation nuclei.

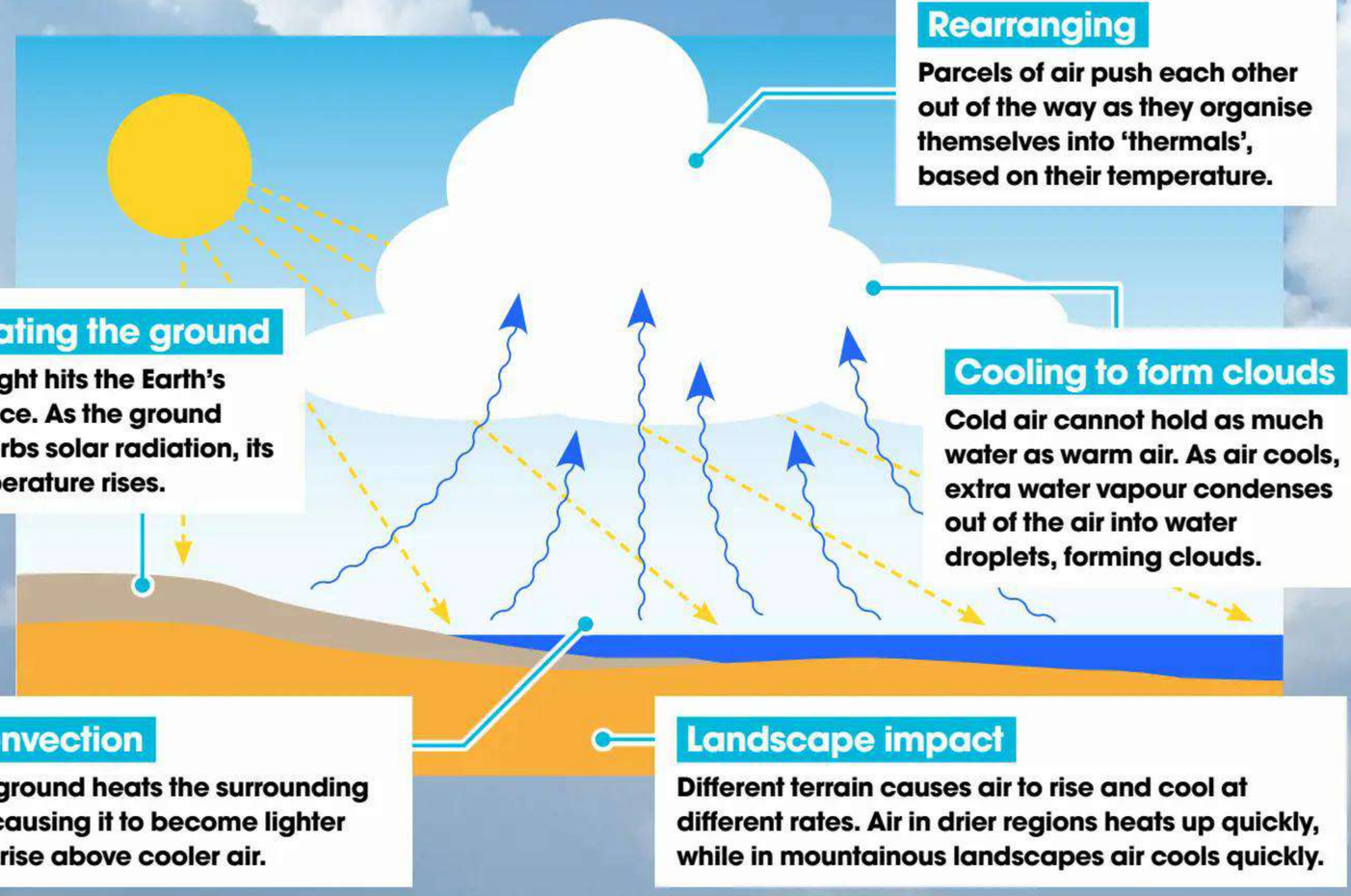
The volume, source and occurrence of clouds differ around the world according to the climate conditions. Near the equator, hot air rises at the most rapid rate, which results in heavy, tropical rainfall.

In desert areas, meanwhile, the extreme lack of moisture means clouds are scarce. With no shade, temperatures soar in the day. But the desert also demonstrates the role clouds play in retaining heat: at night, deserts can become bitterly cold because there is no moisture in the air to hold onto heat.

The mountainous regions of Earth act to obstruct wind flow, which has a fascinating impact on resulting clouds. When air reaches these barriers, it is pushed drastically upwards, creating a unique form of clouds called lenticular clouds. In appearance, these are often compared to a stack of plates, and they are even mistakenly reported as UFOs from time to time.

How do clouds form?

A journey to the clouds: how air carries water into the sky



Clouds that are out of this world

Earth is not the only planet with a cloud-embellished atmosphere. However, not all clouds hold the same properties. On many other planets they are not water-based, although those on Mars are most similar to Earth's as they also contain water. Venus is surrounded by clouds of sulphuric acid. This is due to the atmosphere on the Solar System's hottest planet being about 96 per cent carbon dioxide. They move at speeds of 360kph (224mph) in an easterly circulation around the globe.

Clouds on Venus share some similarities to Earth's, as they are capable of producing lightning. Flybys of the planet detected that lightning occurs at least half the rate that it appears on Earth.

Gas giant Jupiter is surrounded by a 50-km (31-mi) layer of thick clouds. Formed in three decks, its uppermost layer is formed of ammonia crystals, which produce storms hundreds of times more powerful than those on Earth.

All of the planets in the Solar System produce clouds, except for Mercury, the closest planet to the Sun.

Jupiter's Great Red Spot is actually a storm twice the size of Earth that's been raging for 300 years

Cloud-spotting guide

Find out what causes clouds to form and learn how to identify the most common types in our atmosphere

Milky cirrostratus clouds

Cirrostratus clouds cover the sky like a smooth thin veil and can create the appearance of a halo around the Sun. They form high up between 5,490-9,100m (18,000-29,855ft) and indicate that there's moisture at high altitudes.

Curling cirrus clouds

Known as mares' tails, these high-altitude clouds are thin and wispy with a distinct curved shape. They appear in small bands up to 12,190m (40,000ft) above ground and are composed of minute ice crystals.

High-flying cirrocumulus clouds

Appearing as a mass of small, thin puffs of cloud, cirrocumulus clouds develop at high altitudes between 6,100-12,190m (20,000-40,000ft) and are similar in formation to low-level altocumulus clouds. They are composed of ice crystals and supercool water droplets.

6,100m (20,000ft)

Vast altostratus cloud cover

A thin but large cover of featureless altostratus clouds develop between 2,130-5,490m (7,000-18,000ft) above Earth. They diffuse sunlight so shadows won't appear on the ground.

Layered altocumulus clouds

Altocumulus is a middle-level cloud that forms between 1,980-5,490m (6,500-18,000ft) above the ground. Its formation varies between large patchy layers and spaced out flat or wavy shapes. They consist of cool water and ice crystals and often indicate a coming change in weather.

Cumulonimbus thunderstorm clouds

Cumulonimbus clouds have low-lying dark bases that usually form between 335-1,980m (1,100-6,500ft). They are known as thunderstorm clouds and are associated with lightning, thunder, heavy downpours of rain or hail and even tornadoes!

Did you know?
Despite its cotton-like appearance, an average fair-weather cloud weighs more than 400,000kg (62,989st).

2,000m (6,560ft)

Dense stratus clouds

Stratus clouds provide a blanket of grey or white cloud cover and can at times appear low on the ground as a form of fog. They are also usually accompanied by drizzle or snow.

Floating cumulus clouds

Puffy cumulus clouds resemble cauliflowers and their bases form up to 1,980m (6,500ft) above the ground. They are usually seen in fair weather and if they continue to grow in size, they will become thunderous cumulonimbus clouds.

Patchy stratocumulus clouds

Stratocumulus clouds spread like a shallow patchy sheet across the sky. They are low-lying clouds and are formed by shallow convective currents in the atmosphere. Their presence indicates light precipitation and they are usually seen before or after bad weather.

© Getty / The Art Agency

What are lenticular clouds?

Explore the cloud formations that look suspiciously like UFOs

Lenticulars are slow-moving, lens-shaped clouds that form at high altitudes of over 1,980 metres (6,500 feet) above sea level. Their most intriguing feature is that they look a lot like classic B-movie UFOs and are frequently mistaken for extra-terrestrial flying saucers. They are formed when fast-moving air rises and is forced over a topographic barrier, such as a mountain. This interruption in airflow forms a trough in the middle of the cloud, creating their distinctive shape.

These clouds are ideal for adrenaline junkies in hang gliders or sailplanes. Due to their high winds, they help push the aircraft along and create a fast-moving chamber of air for the glider. However, the clouds are a no-go area for aircraft with an engine, as these fast moving wind currents can cause huge turbulence.

Movement
Due to being made up of mostly vertical wind flow (known as vertical oscillations), the clouds stay very still and can often form into stacks.

Height
A huge amount of 'wave lift' is caused by the topographic barrier of a mountain so these types of cloud form thousands of metres/feet in the air.

Airflow
Originating from a strong wind, airflow is always very rapid in a lenticular cloud, making it great fun for hang gliders but not so good for aircraft, which avoid them at all costs!

Shape
The shape is a distinctive saucer structure caused by the vertical wind flow in the centre of the motionless cloud.

Location
Lenticular clouds form almost exclusively near mountains and hills. When a strong wind is interrupted by a tall landmass, a wind-wave pattern is created.

Asperitas clouds

Find out what causes the world's newest cloud formation

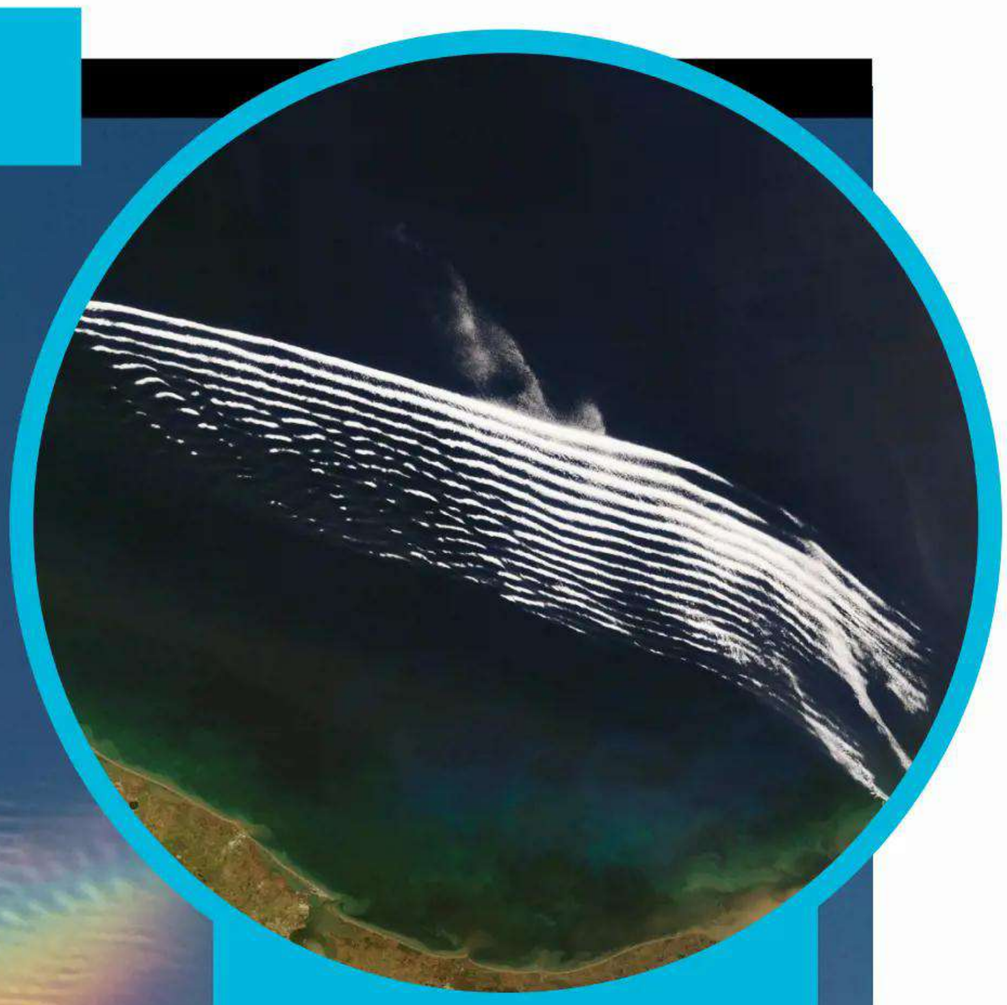
This type of cloud was officially recognised by the UN's World Meteorological Organization in 2017. After being unable to identify the clouds from photos sent in by sky watchers all over the world, the Cloud Appreciation Society proposed that they should be officially classified as *Undulatus asperatus*, inspired by the Latin word for 'roughened' as they look like choppy seas in the sky. Although their formation is not yet entirely understood, some experts believe that they form under the same conditions as mammatus clouds, which look as though they have a series of pouches hanging below them. These occur when ice crystals in the clouds sink, but are too large to evaporate in the air below. To form an asperitas cloud, strong winds then shear the underside of the mammatus cloud to form undulating waves instead of pouches. The clouds were added to the International Cloud Atlas in 2017.

Asperitas clouds have been spotted in England, France, Norway and the USA

© Dreamstime / Flickr; B.J. Bumgarner

What is cloud iridescence?

This happens when small droplets of water or ice crystals in clouds scatter light, appearing as a rainbow of colours. It's not a common phenomenon because the cloud has to be very thin, and even then the colours are often overshadowed by the Sun.

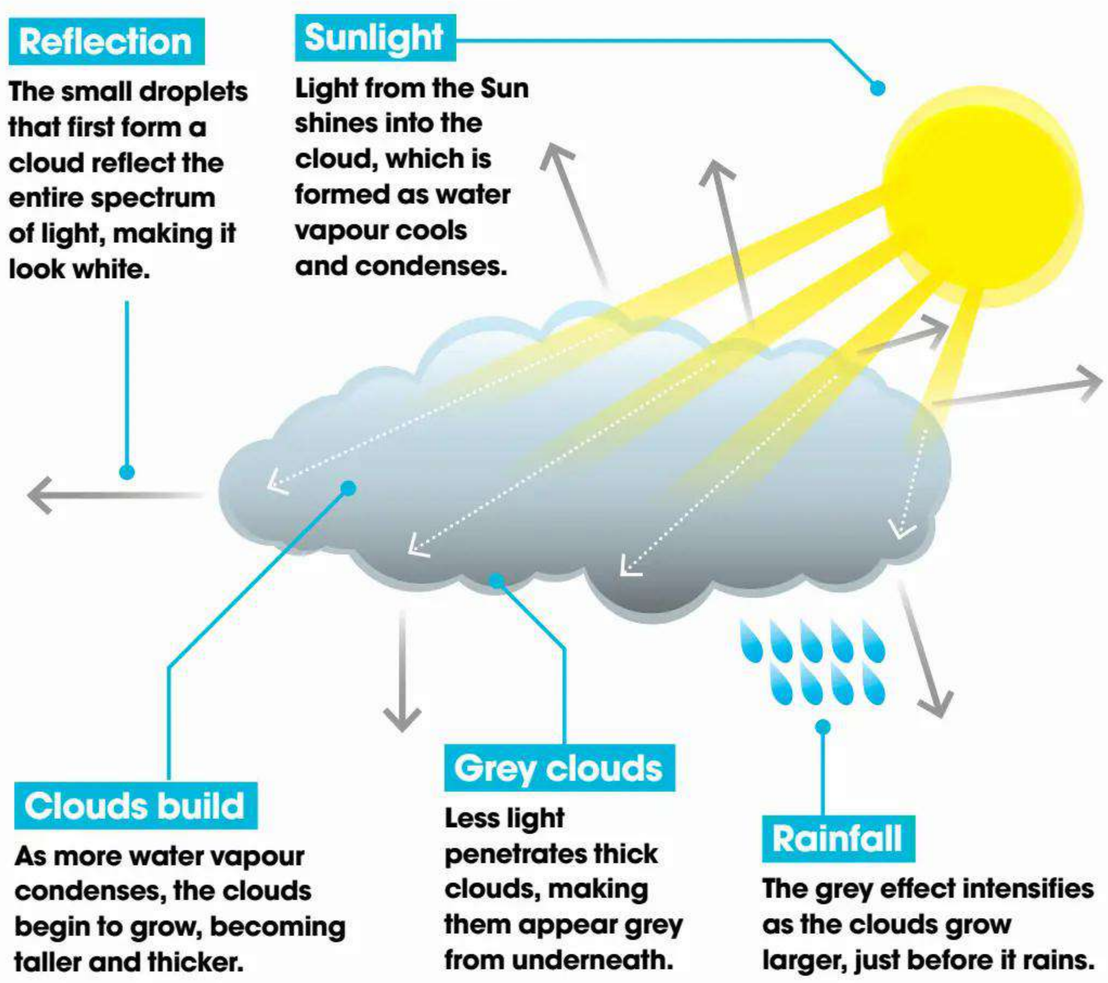


What are gravity wave clouds?

Gravity waves are waves of air moving through a stable area of the atmosphere. The air might be displaced by an updraft or something like mountains as the air passes over. The upward thrust of air creates bands of clouds with empty space between them. Cool air wants to sink, but if it is buoyed again by the updraft, it will create additional gravity wave clouds.

Light and clouds

How sunlight changes how we see the weather



Why are rain clouds grey?

The reason why overcast days are so dismal

To understand why clouds can appear grey, you first need to know why they also appear white. It's all to do with the reflection of light. Clouds are formed when air and water vapour near the ground warms up and rises. As it gets higher, the water vapour condenses, and the droplets join together to form clouds. The more condensation there is, the more droplets there are and the bigger the clouds become. When light from the Sun passes through these large accumulations of water vapour, the droplets scatter the light in all directions. The droplets are small and spread out enough to scatter the entire spectrum of light, which means that they will appear white. As more water droplets gather and the clouds grow larger, less light is able to penetrate through the cloud. What we see from the ground appears grey because less light is being scattered to our eyes. As the water droplets within the cloud get larger, this effect is enhanced, which is why clouds appear much darker just before it rains.

© Dreamstime / Science Photo Library / Shutterstock

Did you know?
Atrapaniebla Brewery in Chile uses fog water from the desert to brew its beer, called Fog Beer.

How fog forms

When water vapour turns to liquid, a murky mass fills the air

Most of the time, clouds hover far above our heads at high altitude. In these colder conditions, the air loses the ability to hold onto water vapour and releases droplets of liquid water. Although it forms in a similar method to clouds, fog extends into lower altitudes and can lie just above the ground. Fog forms when the air's water vapour content is high and conditions are humid. Being close to the ground, the water-filled air reduces visibility and limits the navigation of cars, ships and aircraft. The extent of fog disruption depends on the concentration of water droplets in the air, with the thickest fog usually arising under contrasting conditions, where cold air meets warm air. The foggiest place on the planet is an area of the Atlantic Ocean called Grand Banks, where the northern Labrador Current comes into contact with the warmer Gulf Stream.

Fog reduces aircraft takeoff rates at airports due to severely reduced visibility

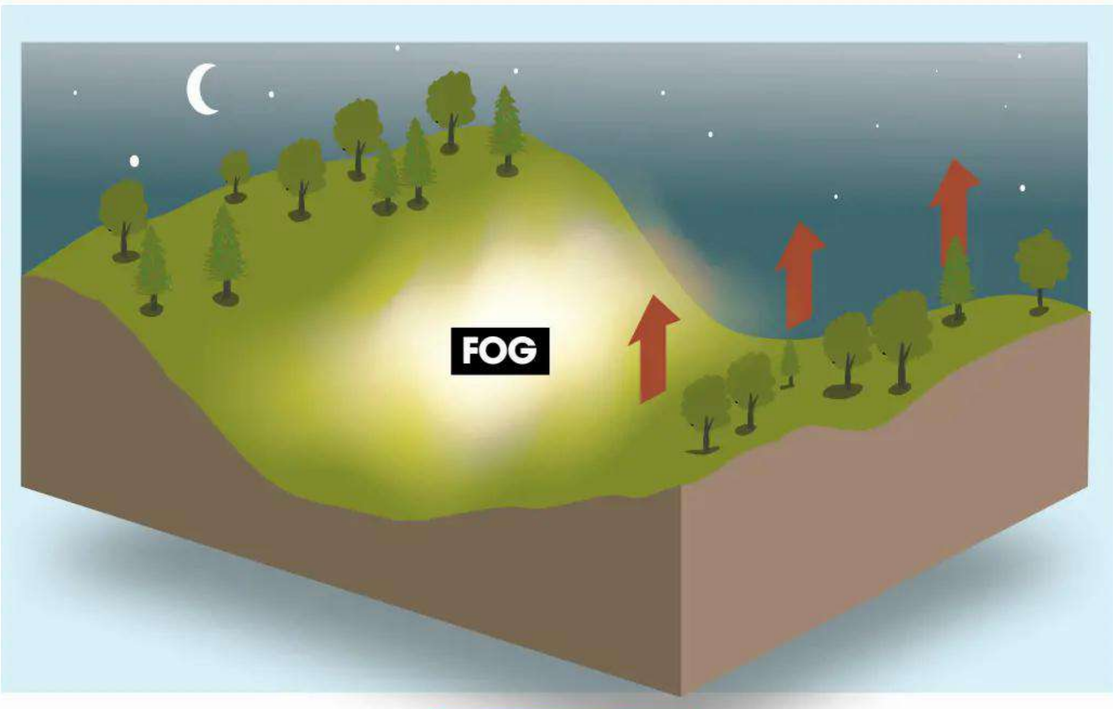
Misty business

Fog and mist appear very similarly in the air as small water droplets that reduce visibility. It's how much the suspended water impacts visibility that determines whether it's classified as fog or mist – fog is thicker than mist. When saturated air prevents you from seeing as far as 1,000m (3,281ft), the term 'fog' is used to describe it. If it's possible to see objects at least 1,000m (3,281ft) in the distance then it is referred to as mist. When walking through foggy air, you will emerge much damper than when travelling in mist.

Hazy days

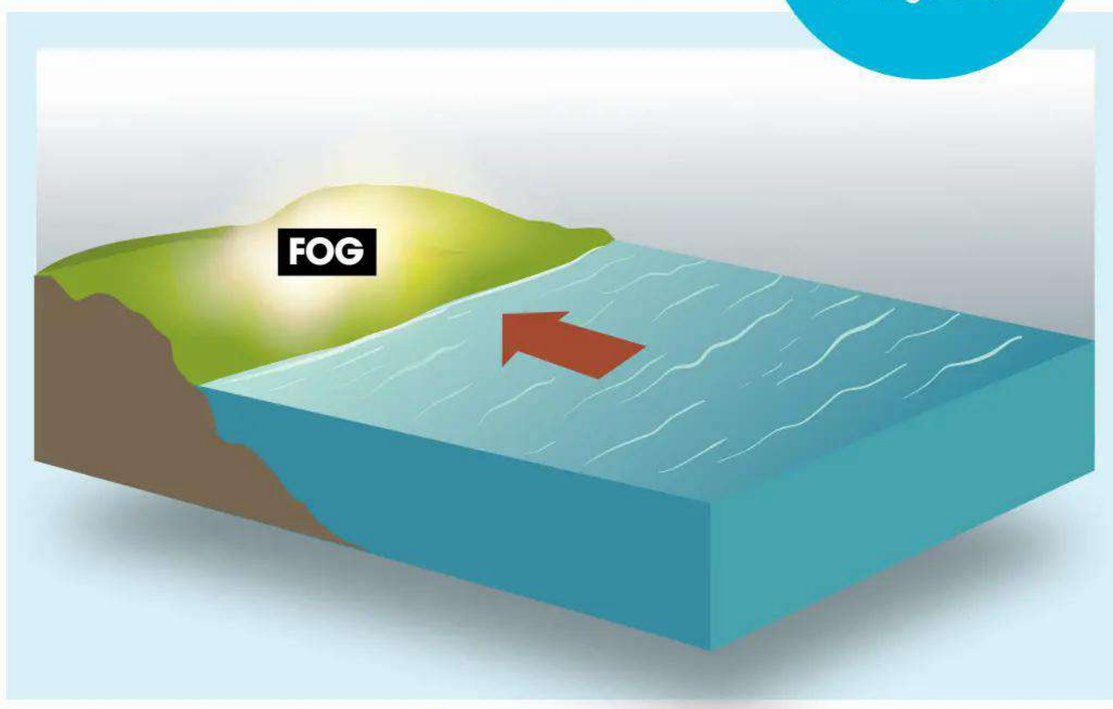
Different environments can lead to diverse forms of this low-lying cloud

Did you know?
Fog creates the illusion that you're driving slower.



Radiation fog

This type of fog forms during mild weather, when there is little wind and the skies are clear of other clouds. The lack of cloud coverage enables Earth's surface heat to escape towards space. The air near the ground cools and condenses into a layer of fog, which grows overnight as the air cools further. When the Sun heats the air again the following day, the fog dissipates.

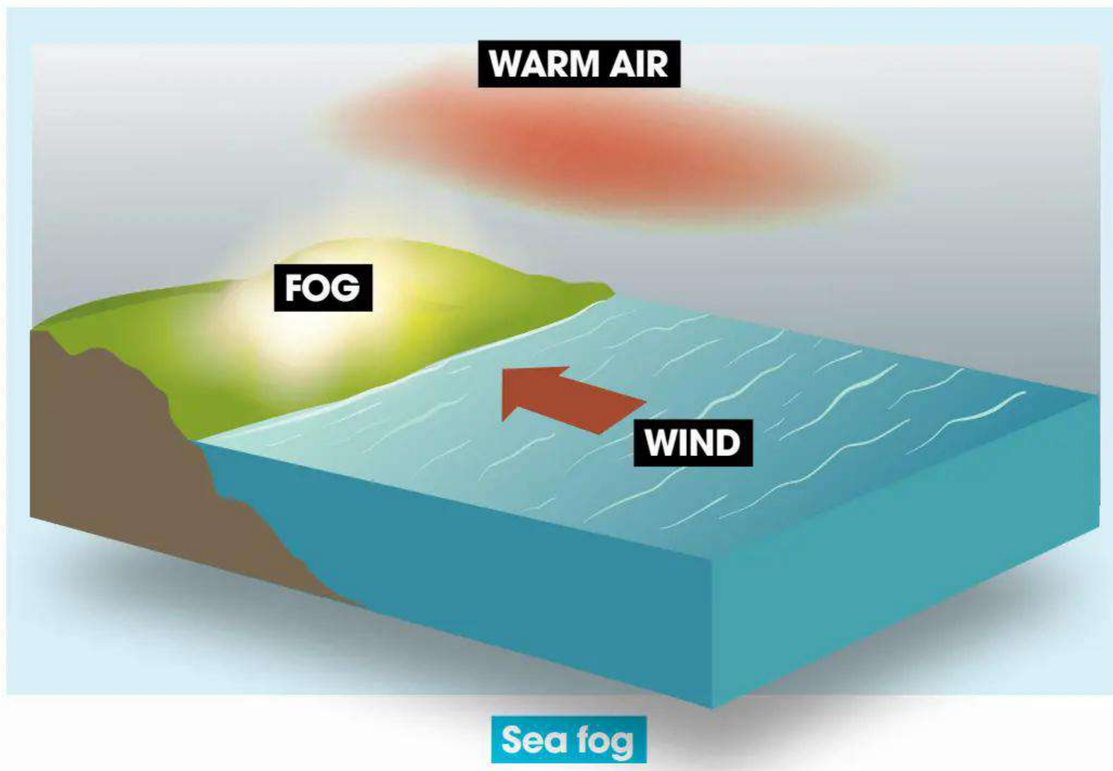


Advection fog

Advection fog forms in a similar way to radiation fog, but is caused by warm air moving horizontally over colder air rather than the vertical loss of surface heat. When the warm air approaches colder ground, it becomes saturated and forms fog.

Frontal fog

This fog is formed when raindrops evaporate in the air. The rain falls through warmer air into cold stable air and forms a fog layer near the ground. When enough rain has saturated the cold layer of air, foggy clouds become visible.



Sea fog

Warm and moist air that forms over a body of water becomes cooler as it's transported with the wind. This cooling causes sea fog to form. When it reaches the warmer air above land it may begin to dissipate.

Fog harvest

When water is suspended in the air in the form of fog, it becomes easier to capture than when it has landed on the ground and seeped through the soil. But to effectively harvest water from foggy landscapes, fog catchers are required. Fog catchers are large screens that are usually assembled in regions with less rainfall. When fog-filled air blows over these screens, the mesh panels catch the water as it condenses, allowing it to drip into containers below. In regions with no local rivers, lakes or glaciers, these screens mean water can be collected on-site rather than having to be imported.

A 40m² (430ft²) fog catcher can capture up to 66l (17.4gal) in one day

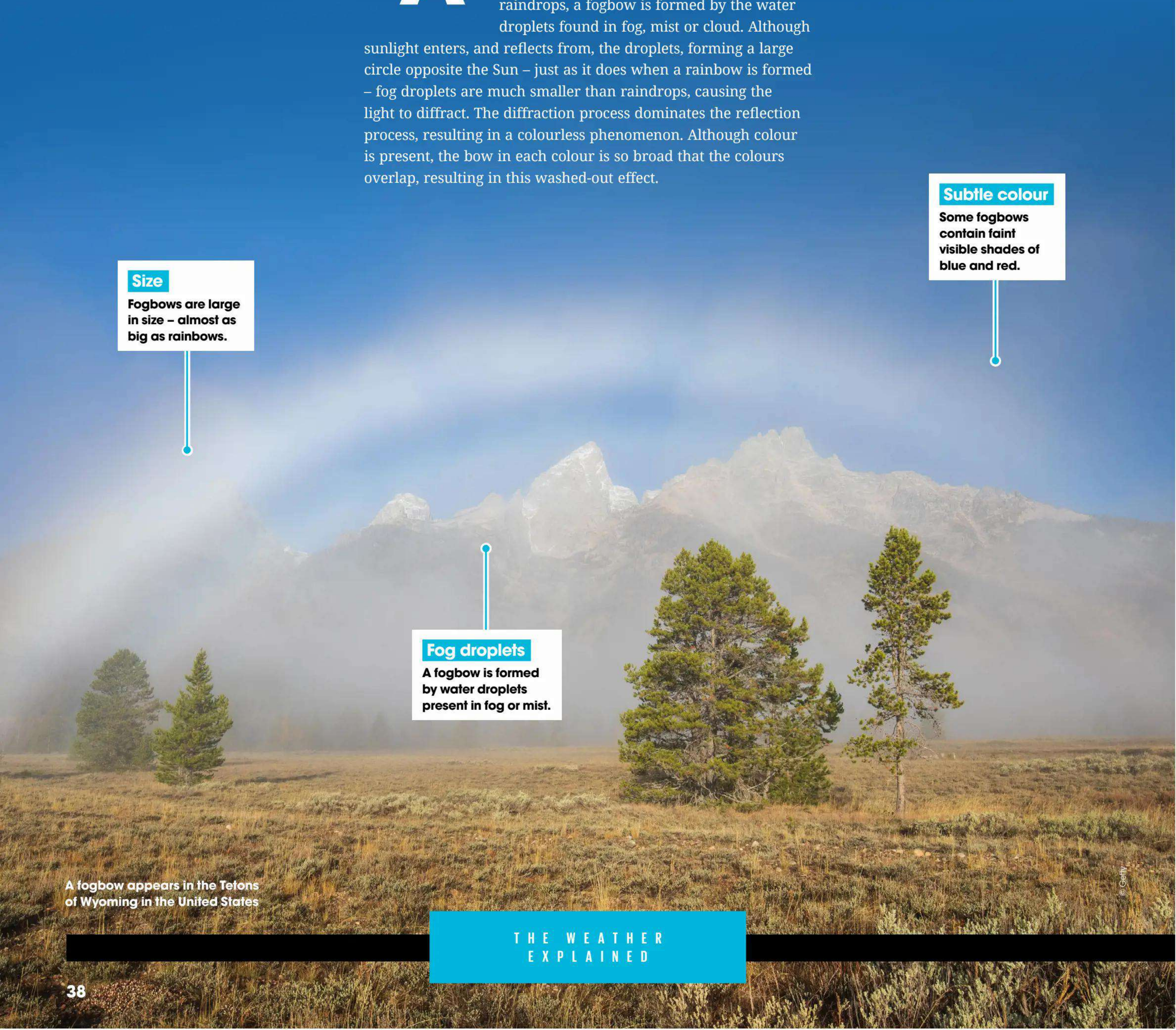
© Alamy / Getty / Shutterstock

Fogbows

Is a fogbow really very different to a rainbow? And how exactly is it formed?

A fogbow is similar to a rainbow by being created from the same process of sunlight refraction and reflection.

However, rather than being formed by raindrops, a fogbow is formed by the water droplets found in fog, mist or cloud. Although sunlight enters, and reflects from, the droplets, forming a large circle opposite the Sun – just as it does when a rainbow is formed – fog droplets are much smaller than raindrops, causing the light to diffract. The diffraction process dominates the reflection process, resulting in a colourless phenomenon. Although colour is present, the bow in each colour is so broad that the colours overlap, resulting in this washed-out effect.



A fogbow appears in the Tetons of Wyoming in the United States

© Getty

What is cloud seeding?

It's possible to make it rain, snow or shine through artficial means. Here's how...

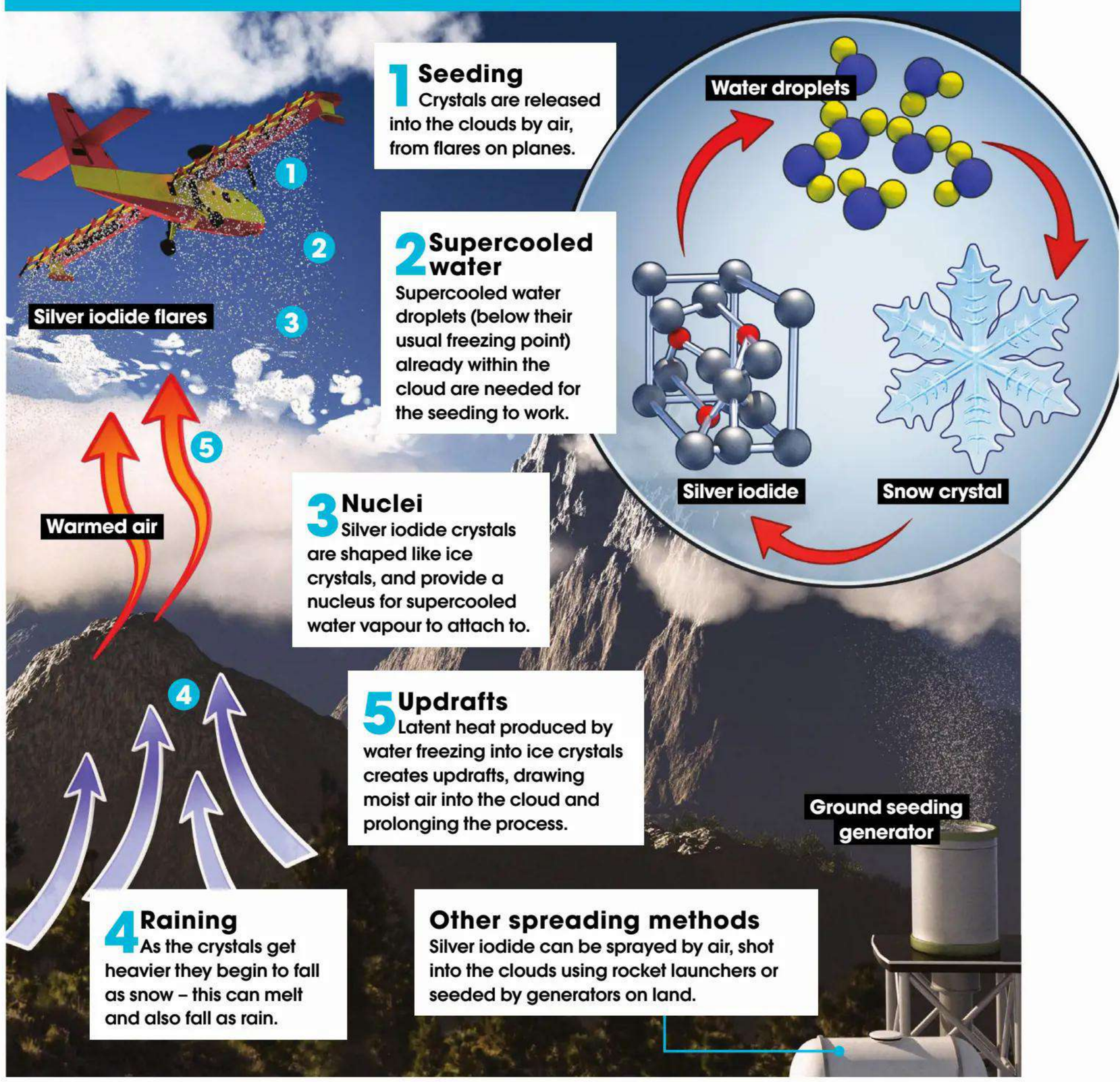
Cloud seeding is a clever way of manipulating the weather to alter how much rain falls. It was first discovered one hot July in New York, 1946. Dr Vincent Schaefer was experimenting with creating clouds and placed a lump of dry ice inside a chamber to cool it down. He noticed that the water vapour in the chamber formed a cloud around the dry ice. This replicates one of the ways that clouds form naturally – as air cools, water vapour clings to tiny particles floating in the air, such as salt and dust, called aerosols. This is known as condensation. As more water vapour sticks to the aerosols, the drops get larger and start sticking to other droplets, forming clouds. Then, as the droplets grow, they become raindrops.

It's this principle that is used in cloud seeding, which can manipulate conditions for both rain and shine. Particles are sprayed into the air to act as nuclei for the water vapour to condense with. The substances used for this include calcium chloride, silver iodide or solid carbon dioxide (dry ice), depending on the climactic conditions of the area. These substances, sprayed from aircraft or launched via rockets, have similar physical structures to ice crystals and other aerosols that act as nuclei for condensing water vapour.

With careful planning, as well as a bit of luck, rain can be produced in dry areas. Seeding can also produce clear skies by ensuring that the rain falls in another area. This was employed by the Chinese government to ensure that the 2008 Beijing Olympic Games weren't washed out by the rainy season.

Make it rain

How dynamic cloud seeding in cool climates can bring the snow



Different types of cloud seeding

Static
Chemicals such as silver iodide are sprayed into clouds. It helps them to use the moisture that's already available more efficiently, allowing them to form additional droplets and produce even more rain.

Dynamic
This uses the latent heat from when cloud seeding causes water vapour to turn into ice crystals. The heat boosts the strength of updrafts and thermals causing the cloud to draw in more moisture and grow larger.

Hygroscopic
This method is used in the tropic regions, because the air is too warm for the other techniques. It uses salts to form nuclei, which go on to become larger droplets. These in turn create heavier clouds and eventually rain.

Aircraft use flares to spread large amounts of seeding stimulants into the clouds

© Wiki: Hagelflieger

Lightning

Capable of breaking down the resistance of air, lightning is a highly visible discharge of electricity capable of great levels of destruction. But how is it formed?

Intense upthrust of volcanic particles can help generate lightning

Lightning occurs when a region of cloud attains an excess electrical charge, either positive or negative, that is powerful enough to break down the resistance of the surrounding air. This process is typically initiated by a preliminary breakdown within the cloud between its high top region of positive charge, large central region of negative charge and its smaller lower region of positive charge.

The different charges in the cloud are caused when water droplets are supercooled within it to freezing temperatures and then collide with ice crystals. This process causes a slight positive charge to be transferred to the smaller ice crystal particles and a negative one to the larger ice-water mixture, with the former rising to the top on updrafts and the latter falling to the bottom under the effect of gravity. The consequence of this is gradual charge separation between the upper and lower parts of the cloud.

This polarisation of charges forms a channel of partially ionised air – ionised air is that in which neutral atoms and molecules are converted to electrically charged ones – through which an initial lightning stoke (referred to as a 'stepped leader') propagates down through towards the ground. As the stepped leader reaches the earth, an upwards connecting discharge of the opposing polarity meets it and completes the connection, generating a return stroke that due to the channel now being the path of least resistance, returns up through it to the cloud at one-third the speed of light and creating a large flash.

Did you know?
The peak temperature of a lightning bolt's return-stroke channel is 30,000°C (54,032°F).

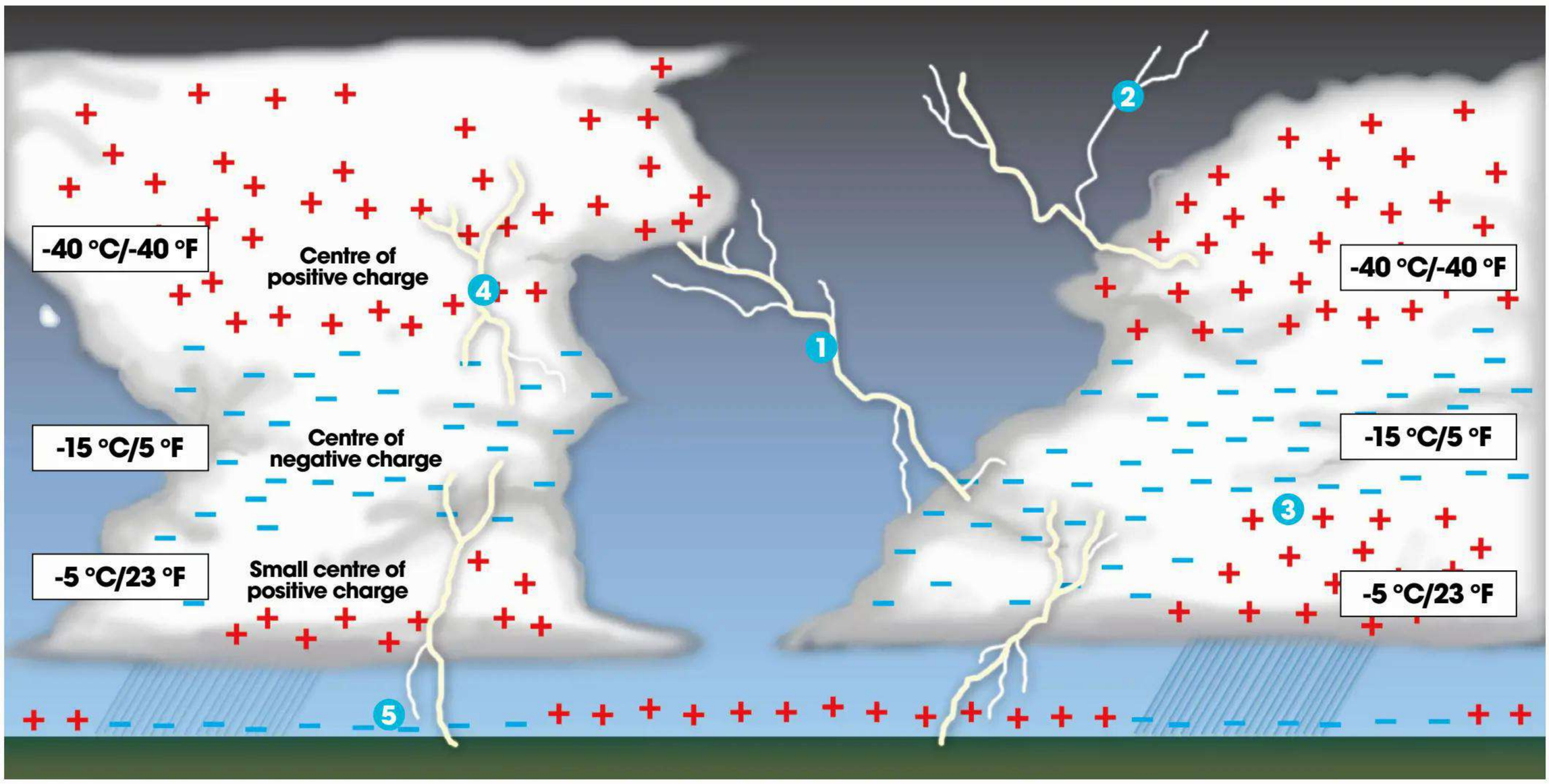
This leader-return stroke sequence down and up the ionised channel through the air commonly occurs three or four times per strike, faster than the human eye is capable of perceiving. Further, due to the massive potential difference between charge areas – often extending from ten to 100 million volts – the return stroke can hold currents up to 30,000 amperes and reach 30,000 degrees Celsius (54,032 degrees Fahrenheit). Typically the leader stroke reaches the ground in ten milliseconds and the return stroke reaches the instigating cloud in 100 microseconds.

Lightning, however, does not just occur between clouds (typically cumulonimbus or stratiform) and the ground, but also between separate clouds and even intra-cloud. In fact,

Explaining the formation of lightning

1 Cloud-to-cloud
As with cloud-to-ground, cloud-to-cloud lightning discharges occur between polarised areas of differing charge, however here the ionised channel runs between clouds instead of a cloud to the ground.

2 Cloud-to-air
Similar to cloud-to-cloud, cloud-to-air strikes tend to emanate from the top-most area of a cloud that is positively charged, discharging through an ionised channel directly into the air.



5 Cloud-to-ground
Cloud-to-ground lightning occurs when a channel of partially ionised air is created between areas of positive and negative charges, causing a lightning stroke to propagate downward to the ground.

4 Intra-cloud
Intra-cloud lightning is the most frequent type worldwide and occurs between areas of differing electrical potential within a single cloud. It is responsible for most aeroplane-related lightning disasters.

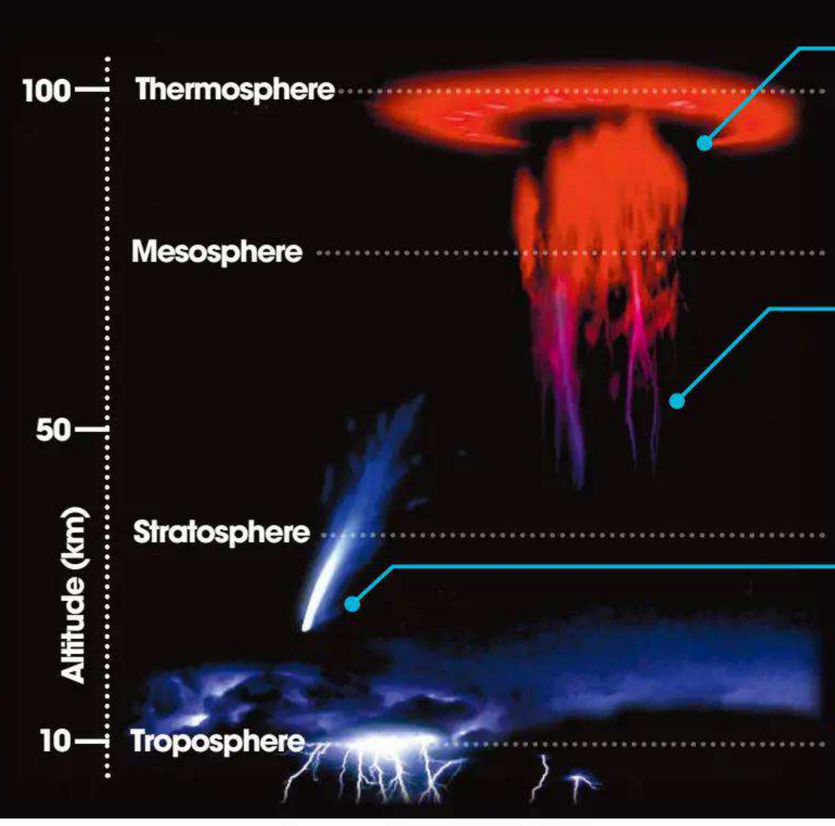
3 Charge differential
Clouds with lightning-generating potential tend to consist of three layers of charge, with the top-most part a centre of positive charge, the middle a centre of negative charge, and the bottom a secondary small centre of positive charge.

75 per cent of all lightning strikes are cloud-to-cloud or intra-cloud, with discharge channels forming between areas of positive and negative charges between and within them. In addition, much lightning occurs many kilometres/miles above the Earth in its upper atmosphere, ranging from types that emanate from the top of clouds, to those that span hundreds of kilometres/miles in width.

Interestingly, despite the high frequency of lightning strikes and their large amount of contained energy, current efforts by the scientific community to harvest its power have been fruitless. This is mainly caused by the inability of modern technology to receive and store such a large quantity of energy in such a short period of time, as each strike discharges in mere milliseconds. Other issues preventing lightning's use as an energy source include its sporadic nature (it rarely strikes the same place twice) and the difficulties involved in converting high-voltage electrical power delivered by a strike into low-voltage power that can be stored and used commercially.

Atmospheric lightning

Unseen apart from by satellites, a major part of the world's annual lightning is generated in Earth's upper atmosphere



Elves
Vast 402-km (250-mi) wide flattened discs of light, elves occur above low-lying thunderstorms by the excitation of nitrogen molecules due to electron collisions in the atmosphere.

Sprites
Sprites are caused by the discharges of positive lightning from thunderclouds to the ground. They vary in colour from red to blue and appear akin to large jellyfish.

Blue jets
Emanating from the top of cumulonimbus clouds and stretching in a cone shape up into the stratosphere and mesosphere, blue jets are caused by intense hail activity within a storm.

© Science Photo Library

Lightning types

Far from uniform, lightning is an unpredictable phenomenon

Bead lightning

A type of cloud-to-ground lightning where the strike seems to break up into smaller, super-bright sections (the beads), lasting longer than a standard discharge channel.

Frequency: **Rare**

Ribbon lightning

Only occurring in storms with high cross winds and multiple return strokes, ribbon lightning occurs when each subsequent stroke is blown to the side of the last, causing a visual ribbon effect.

Frequency: **Quite rare**

Staccato lightning

A heavily branched cloud-to-ground lightning strike with short duration stroke and incredibly bright flash.

Frequency: **Common**

© Scotto Bear

Sheet lightning

A generic term used to describe types of cloud-to-cloud lightning where the discharge path of the strike is hidden from view, causing a diffuse brightening of the surrounding clouds in a sheet of light.

Frequency: **Common**

© Christian Artntzen

Megalightning

A term commonly used when referring to upper-atmospheric types of lightning. These include sprites, blue jets and elves and occur in the stratosphere, mesosphere and thermosphere.

Frequency: **Frequent**

Ball lightning

Ball lightning is a highly luminous, spherical discharge. Although video and photo evidence is very rare, according to few eyewitnesses it lasts multiple seconds and can move on the wind.

Frequency: **Very rare**

What happens when you get struck by lightning?

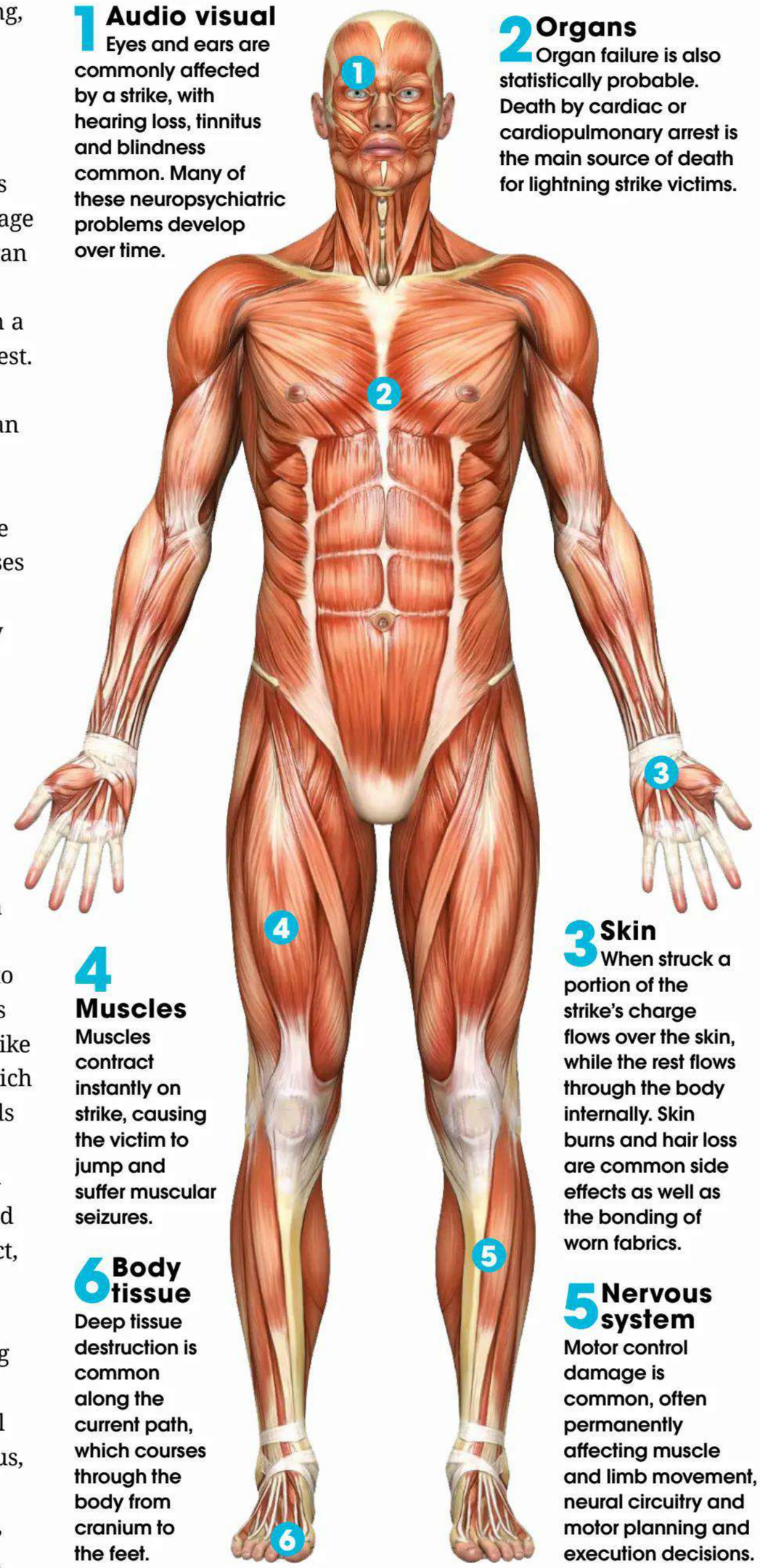
The parts of the body that feel the effect if struck by lightning

When a human is hit by lightning, part of the strike's charge flows over the skin – referred to as external flashover – and part of it goes through them internally. The more of the strike that flows through, the more internal damage it causes. The most common organ affected is the heart, with the majority of people who die from a strike doing so from cardiac arrest.

Deep tissue destruction along the current path can also occur, most notably at the entrance and exit points of the strike on the body. Lightning also causes its victims to physically jump, which is caused by the charge contracting the muscles in the body instantaneously.

Burns are the most visible effect of being struck by lightning, with the electrical charge heating up any objects in contact with the skin to incredible levels, causing them to melt and bond with the human's skin. Interestingly, however, unlike industrial electrical shocks – which can last hundreds of milliseconds and tend to cause widespread burns over the body – lightning-induced burns tend to be centred more around the point of contact, with a victim's head, neck and shoulders most affected.

Post-strike side effects of being struck by lightning range from amnesia, seizures, motor control damage, hearing loss and tinnitus, through to blindness, sleep disorders, headaches, confusion, tingling and numbness. Further, these symptoms do not always develop instantaneously, with many – notably neuropsychiatric problems (vision and hearing) – developing over time.



1 Audio visual
Eyes and ears are commonly affected by a strike, with hearing loss, tinnitus and blindness common. Many of these neuropsychiatric problems develop over time.

2 Organs
Organ failure is also statistically probable. Death by cardiac or cardiopulmonary arrest is the main source of death for lightning strike victims.

3 Skin
When struck a portion of the strike's charge flows over the skin, while the rest flows through the body internally. Skin burns and hair loss are common side effects as well as the bonding of worn fabrics.

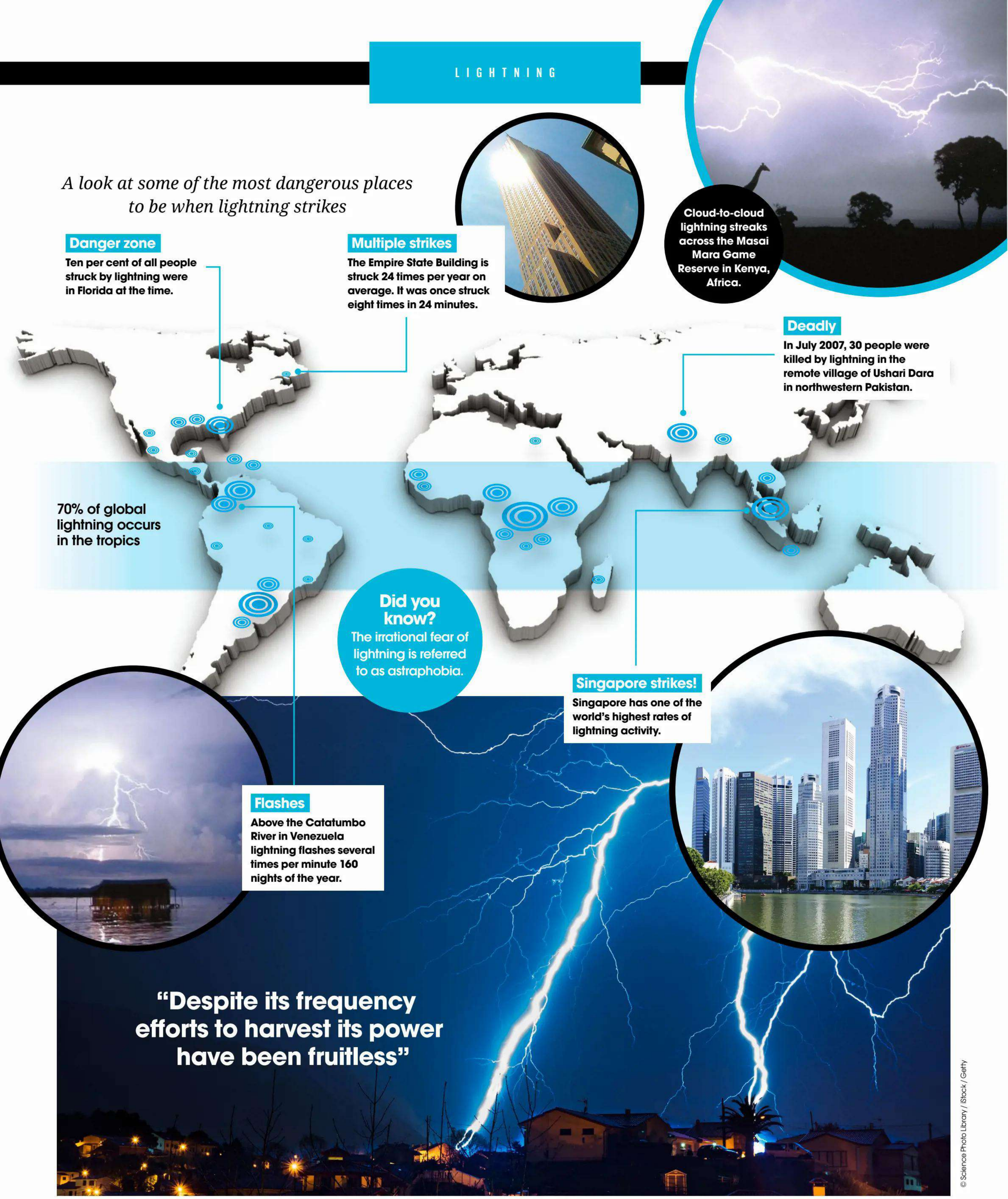
4 Muscles
Muscles contract instantly on strike, causing the victim to jump and suffer muscular seizures.

5 Nervous system
Motor control damage is common, often permanently affecting muscle and limb movement, neural circuitry and motor planning and execution decisions.

6 Body tissue
Deep tissue destruction is common along the current path, which courses through the body from cranium to the feet.

"According to the Met Office, there are around 44 lightning strikes every second"

A look at some of the most dangerous places to be when lightning strikes



Cloud-to-cloud lightning streaks across the Masai Mara Game Reserve in Kenya, Africa.

Danger zone

Ten per cent of all people struck by lightning were in Florida at the time.

Multiple strikes

The Empire State Building is struck 24 times per year on average. It was once struck eight times in 24 minutes.

Deadly

In July 2007, 30 people were killed by lightning in the remote village of Ushari Dara in northwestern Pakistan.

Did you know?

The irrational fear of lightning is referred to as astraphobia.

Singapore strikes!

Singapore has one of the world's highest rates of lightning activity.

Flashes

Above the Catatumbo River in Venezuela lightning flashes several times per minute 160 nights of the year.

"Despite its frequency efforts to harvest its power have been fruitless"

© Science Photo Library / iStock / Getty

What causes wind?

How the uneven heating of our planet produces everything from a light breeze to a full-force gale

Earth's atmosphere is structured into five main layers. From the closest to farthest from Earth's surface, these are the troposphere, stratosphere, mesosphere, thermosphere and exosphere. The air gets thinner as the distance from the planet's surface increases, but each of these atmospheric layers displays turbulence. Air particles are constantly churned both vertically and horizontally; this turbulence is also known as wind. The wind we experience when we venture outside is in the troposphere, and it can vary extremely in temperature and strength. But what causes these tiny particles to move so ferociously, and in unison, that the feeling of wind hitting the skin can be as strong as a slap in the face?

Air changes position in the atmosphere as its pressure alters. When its particles gain heat – and energy – they move more, creating larger gaps between particles and reducing density. This causes the warmer air to rise above denser particles and creates flows of air.

Earth's atmospheric pressure isn't uniform, so the atmosphere is never going to be still. The further from the equator you are, the lower the air pressure will become at the same altitude. Winds that blow due to these differences are called planetary or prevailing winds. Other winds, which aren't permanent, are those created by changes in seasons, called periodic winds, and winds created by local weather and terrain.

Strong winds can be life-threatening and damaging to trees and buildings, but the presence of wind also benefits the planet. In different layers of the atmosphere, water vapour, energy and other substances are distributed by the moving air. At ground level, this movement keeps people and animals cool, distributes the seeds of plants and generates renewable electrical energy.

The wind cycle

A rush of air is generated by the planet's varied surfaces

Did you know?
The term 'katabatic winds' comes from the Greek word katabasis, meaning 'going down'.

2 Rising air
The ground heats the surrounding air, causing it to rise.

3 Sinking air
As air cools, it sinks towards the ocean surface.

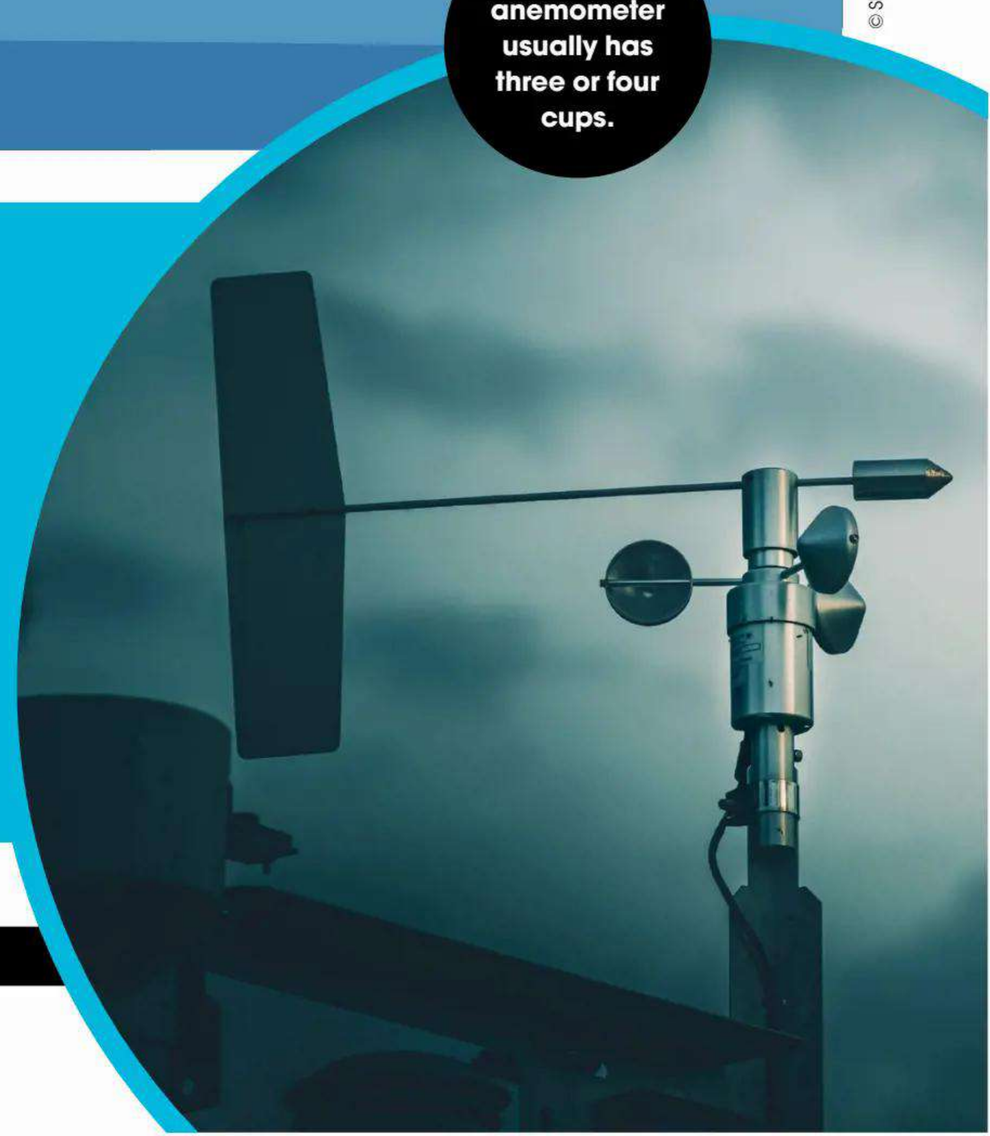
1 Land heat
The Sun heats the land more quickly than the oceans.

4 Coastal wind
As the air above ground is heated and rises, colder air from the ocean moves in to replace it. This moving air is wind.

5 Day and night
Winds are reversed in the night. When the Sun goes down, the air cools quicker over land, causing it to travel in the opposite direction.

Did you know?
The Beaufort wind force scale was invented in 1805.

© Shutterstock / Getty



An anemometer usually has three or four cups.

How meteorologists predict and measure wind

When predicting weather, meteorologists rely on a variety of tools to collect extensive data about the atmosphere. Satellites can track the motion of clouds by producing a series of images. From this information, forecasters can predict where the winds will travel next. Many instruments can be used to collect data about wind. Cup anemometers are tools that rotate at rates proportional to the speed of wind. To achieve this, specially designed conical cups are attached to the instrument's axle for the wind to blow into. As this happens, the cups rotate. Because wind intensity can change quickly in short periods of time, it's measured as the average speed and direction of wind over a ten-minute period. Wind is defined as a gale when an average speed of 63 kilometres per hour (39 miles per hour) is achieved in this period.

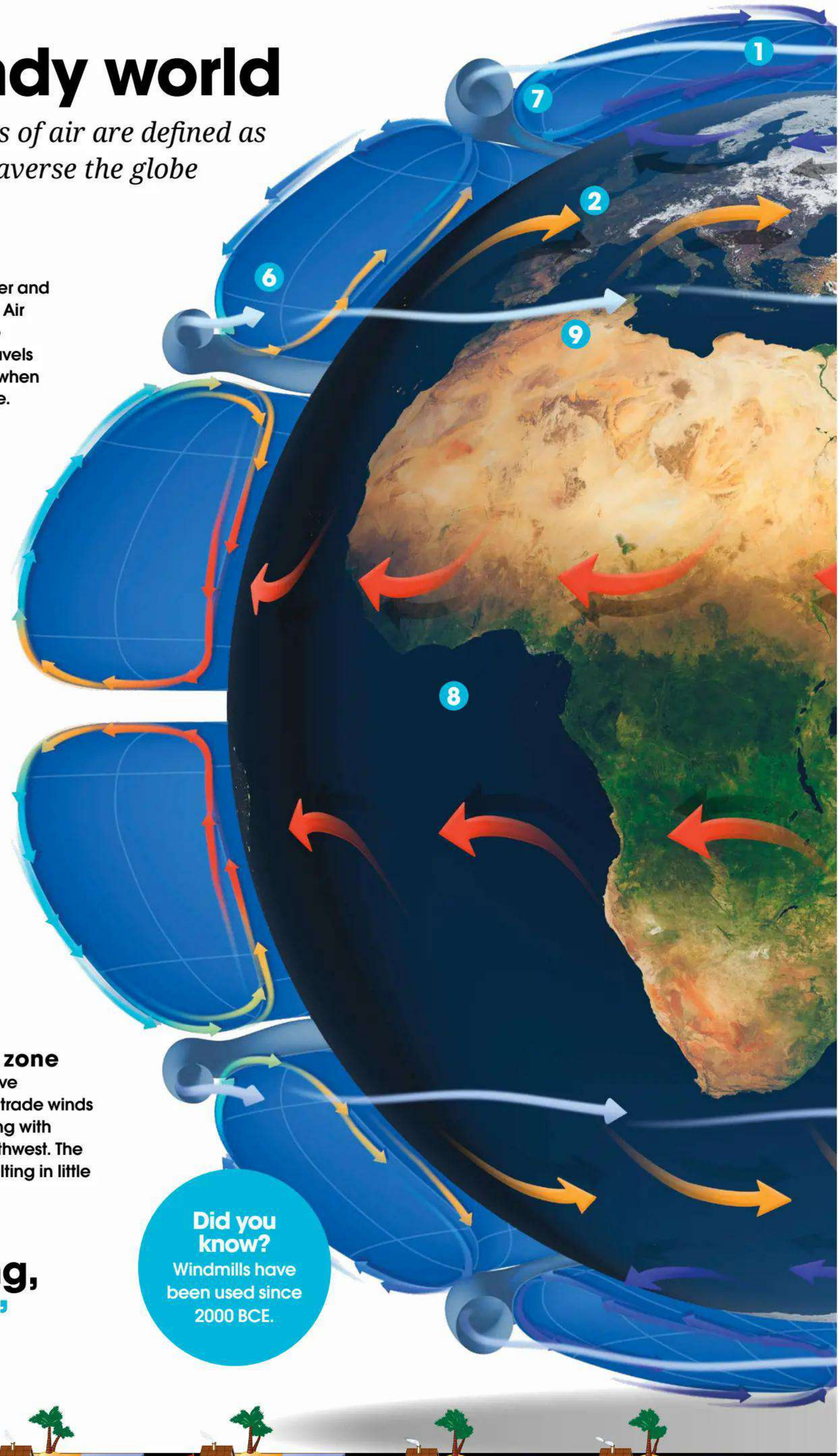
The windiest place on Earth

Every winter, winds in Antarctica reach speeds of over 161kph (100mph. The continent experiences such strong gusts as a result of katabatic winds. Katabatic winds are created by the extremely cold temperatures of Antarctica. The cold, dense air lying above the icy surface travels downwards towards the coast due to gravity and pressure differences between dense and thinner air. Commonwealth Bay, Antarctica is regarded as the windiest place on the planet. In this 60-km (37-mi) wide region, winds regularly travel at more than 241kph (150mph). Due to the bay's crescent shape, katabatic winds travelling into it are forced into its narrow space. This increases wind speed as air passes through, contributing to the bay's average annual wind speed of 81kph (5mph).

Adélie penguins use Commonwealth Bay as a breeding ground despite the extreme winds

A windy world

How streams of air are defined as they traverse the globe



7 Polar cell
Polar cells are smaller and weaker than other cells. Air sinks when reaching the highest latitudes and travels towards lower latitudes when it reaches Earth's surface.

2 Polar front
The region between tropical air and polar air is called the polar front.

6 Mid-latitude cell
The airflow in this cell moves in the reverse direction to that in the Hadley cells. Air moves towards the poles near Earth's surface and towards the equator at higher altitudes.

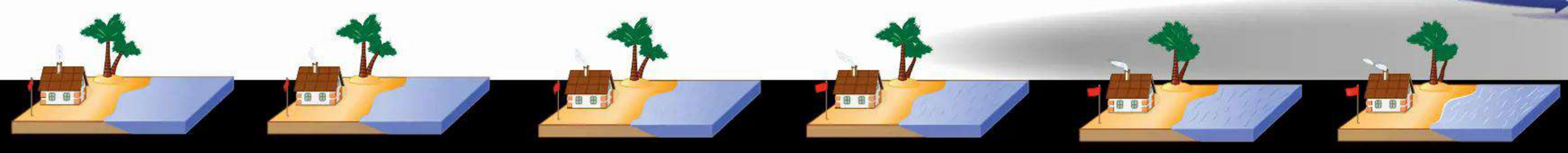
8 Intertropical convergence zone
About five degrees above and below the equator, trade winds move southwest, colliding with trade winds moving northwest. The air moves upwards, resulting in little surface wind here.

Did you know?
Windmills have been used since 2000 BCE.

"Strong winds can be life-threatening, but wind also benefits the planet"

The Beaufort scale

The numbers of this scale correlate to the force of wind



0 Calm and still
<0kph (0mph) Smoke rises vertically.

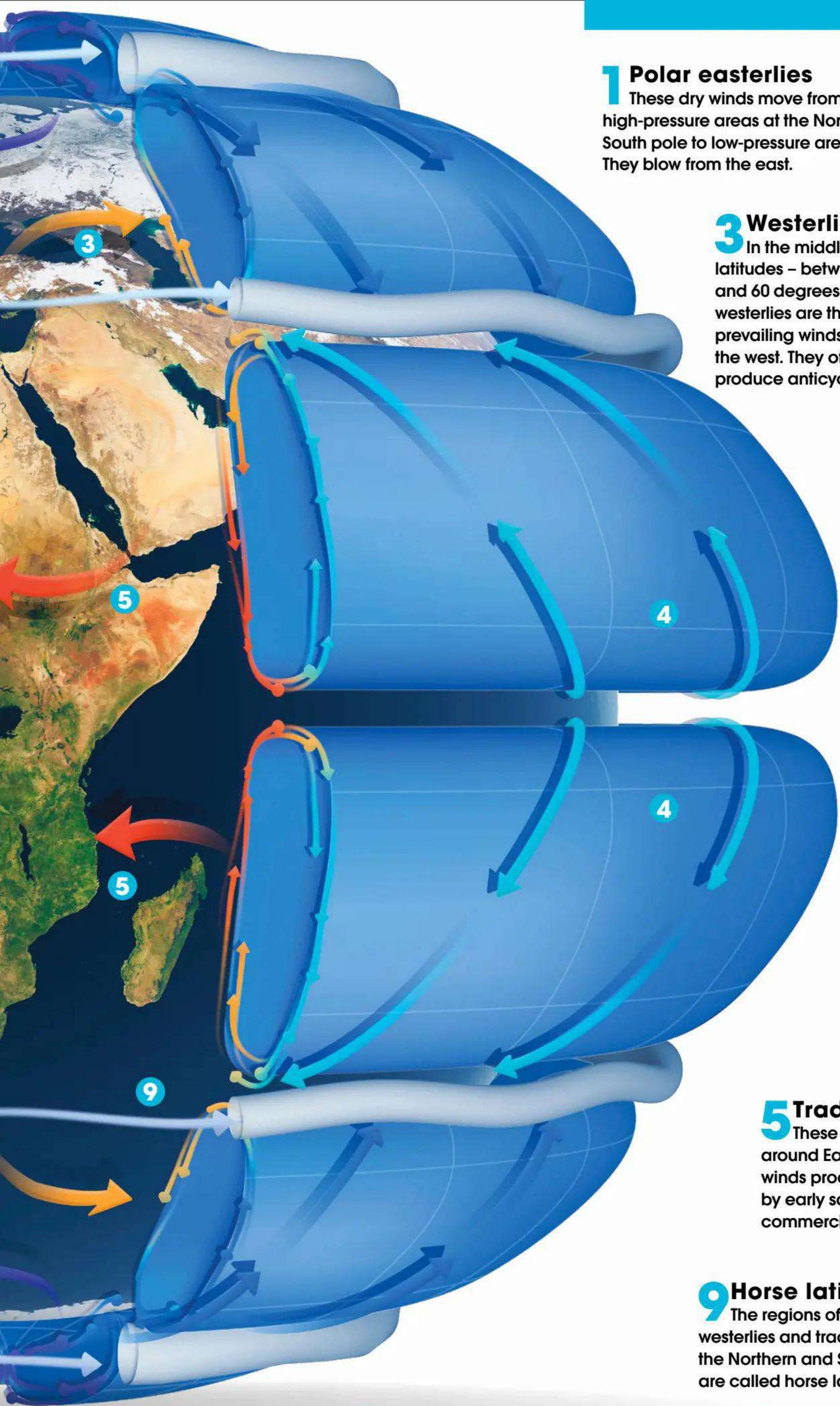
1 Light air
1-5kph (1-3mph) Wind direction can be shown by smoke drift. The sea is rippled.

2 Light breeze
6-11kph (4-7mph) Leaves rustle on trees and wind is strong enough to move wind vanes.

3 Gentle breeze
12-19kph (8-12mph) Trees' twigs constantly move. Small flags fly in the wind.

4 Moderate breeze
20-29kph (13 -18mph) Dust and small branches can be lifted. Small waves form in the sea.

5 Fresh breeze
30-39kph (19-24 mph) Moderate-sized waves form. Small trees sway.



1 Polar easterlies
These dry winds move from cold, high-pressure areas at the North and South pole to low-pressure areas. They blow from the east.

3 Westerlies
In the middle latitudes – between 30 and 60 degrees – westerlies are the prevailing winds from the west. They often produce anticyclones.

Hurricanes rotate clockwise in the Southern Hemisphere and anticlockwise in the Northern Hemisphere due to the rotation of Earth

Did you know?
The largest hurricane on record had a diameter of around 2,221km (1,380 mi).

4 Hadley cells
These cells make up the global tropical atmospheric circulation. Air rises near the equator and moves towards the poles.

5 Trade winds
These easterly winds blow around Earth near the equator. Trade winds produce ocean currents, used by early sailing ships and modern commercial ships for quicker journeys.

9 Horse latitudes
The regions of calm air where westerlies and trade winds meet in both the Northern and Southern Hemisphere are called horse latitudes.

5 Facts about wind patterns

1 Jet streams
Earth has four main jet streams. These strong and narrow bands of wind blow from west to east across the globe.

2 Hurricanes and cyclones
These large, spiralling storms produce winds of at least 119kph (74mph). These systems form above warm water and can move over land to cause devastation.

3 Tornadoes
These narrow columns of air rotate violently. Tornado winds can travel at 322kph (200mph) and connect thunderstorms to the ground.

4 Blizzards
When storms carry and release considerable volumes of snow, they are known as blizzards. They greatly reduce visibility and have winds exceeding 56kph (35mph).

5 Typhoons
This wind pattern is similar to a hurricane, but forms in the northwest Pacific Ocean. Japan, the Philippines and China are the largest countries affected by typhoons.

6 Strong breeze
40-49kph (25-31mph)
Large branches move and large waves form.

7 Near gale
50-61kph (32-38mph)
It is difficult to walk against the wind. Foam is blown across the sea.

8 Gale
62-74kph (39-46mph)
Twigs break from trees.

9 Strong gale
75-88kph (47-54mph)
Buildings can be damaged, such as roof slates being blown off.

10 Storm
89-102kph (55-63mph)
Trees are uprooted. Damage is caused to buildings and other structures.

11 Violent storm
103-117kph (64-72mph)
Widespread structural damage. The sea is covered in white foam and large waves.

12 Hurricane
118kph+ (73+mph)
Ocean foam and spray fills the air. There is significant structural damage.

© Getty / Science Photo Library

The wind superhighway

How the atmosphere creates Earth's air currents high in the sky

Polar jet stream

High in the atmosphere, the polar jet stream is the world's most powerful. It moves south in the winter and north in the summer.

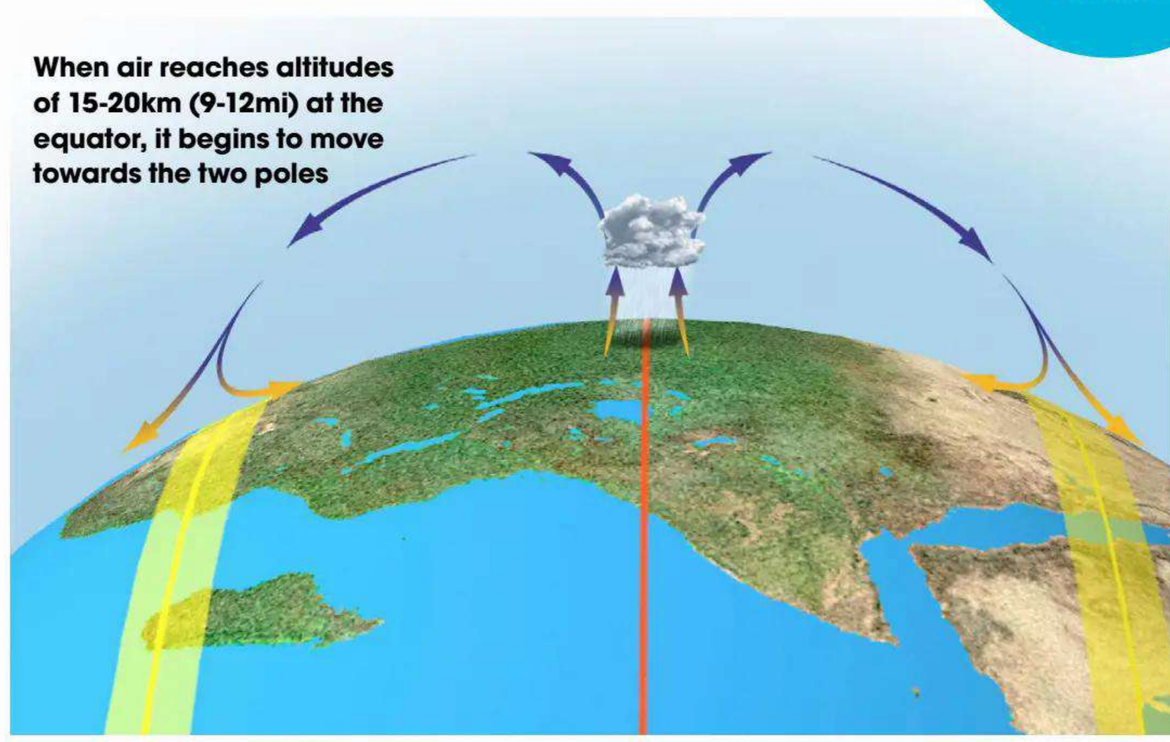
Did you know?
Jet streams on Jupiter are 100 to 1,000 times wider than any found on Earth.

Air in the atmosphere is constantly on the move. Composed of several layers – from just above ground level to high in the sky – air particles are subjected to varying pressures and energy distribution. Whether in slight movements to carry heat from the equator towards the poles or through strong currents called jet streams, air is on a continuous journey often impossible to see.

Earth's atmosphere is divided into five main layers, with the troposphere lying closest to the surface. Ranging from six to 20 kilometres (3.7 to 12.4 miles) in thickness, the troposphere consists of two layers: the upper layer, known as the free atmosphere, and the lower layer, known as the planetary boundary layer. The bottom layer begins at the Earth's surface and stretches up around 1,000 metres (3,281 feet). This may sound like a big space, but it is actually relatively thin. The air moving within the layer can be altered greatly by changing conditions in the landscape and wind-altering pressure above the layer.

Jet streams are usually found in the upper layers of the atmosphere. In the form of thin bands of strong wind, they are created between two air masses of different temperatures. The varying density between masses creates a horizontal pressure difference. Wind tries to flow from high to low pressures, but the planet's rotation forces the air from west to east, flowing around the masses rather than between them. Four main jet streams circulate our planet; two north of the equator and two south of the equator. The ones closest to the centre of the globe are called the subtropical jet streams, and those closest to the poles are the polar jet streams. Occasionally the subtropical and polar jet stream meet, forming a boundary between the two extremely different air masses called the polar front.

The greater the contrast in temperature across the polar front, the stronger the jet stream. Typically, this is at its strongest during the winter months. The area stores large amounts of potential energy, which is often converted into kinetic energy in the form of extratropical cyclones.



When air reaches altitudes of 15-20km (9-12mi) at the equator, it begins to move towards the two poles

Core strength

The centre of jet streams have the greatest strength. Surrounding air moves with the current's direction, but at lesser speeds. Compared to a river's flow, they are often referred to as 'rivers of air'.

Creating UK climates

The location of jet streams are heavily analysed when predicting incoming weather. In the UK, the position of the polar jet stream determines factors such as where storms will arise. Warm winds that travel over water usually collect some, holding onto it until moving over colder climates, when it condenses into rain. When the polar jet stream is above the country, the weather is usually mild as a result. Contrastingly, if the air current crosses through the land, this is when storms are brought along. Heavy snow is often seen in the south of the UK when the jet streams are carried below the country. Continental Europe gets the majority of the stormy weather in this circumstance, but wind from low-pressure systems heading towards the south pull in the cold air from Europe.

The period of time a weather type will persist is dependant on the type of jet stream in motion. The faster-moving zonal streams will carry air quickly, passing the storm over in a short time. In more meridional currents, the stretched, latitudinal path slows progression, increasing the time taken for the weather front to pass.

When the polar jet stream travels over the UK, it's wetter and windier

How do air currents move?

Follow the jet streams journeying around the globe

Polar jet stream · Subtropical jet stream

Coriolis effect

The rotation of Earth on its axis means that it turns faster at the equator than at the poles. This deflects air currents towards the North and South, stopping jet streams flowing at the centre.

Zonal flow

The straighter the route taken by a jet stream, the more zonal it is said to be.

Meridional flow

Jet streams that take a slower, meandering movement around the globe are described as meridional.

Subtropical jet stream

This strong current travels at lower latitudes and higher elevations to the polar jet stream.

How air currents alter the weather

Bringing Britain's rain

The North Atlantic Current, running from the Gulf Stream, results in parts of the UK being warmer than countries to the east on the same longitude. In winter however, it brings more rain, as it directs low pressure towards the UK.

Diverting US hurricanes

In autumn, a strong jet stream over the United States carries incoming hurricanes on an eastward path, preventing them from moving north along the Gulf Coast or Atlantic Seaboard.

Altering tropical storms

If a jet stream travelling over tropical waters suddenly dips southward, it can cause hurricanes in the area to accelerate in speed, or sometimes tears them completely apart.

Creating tornadoes

Particularly in some North American states, such as Oklahoma, jet streams play a major role in creating super cells, the huge and frequently dramatic storm systems lower in the atmosphere that can lead to the formation of tornadoes.

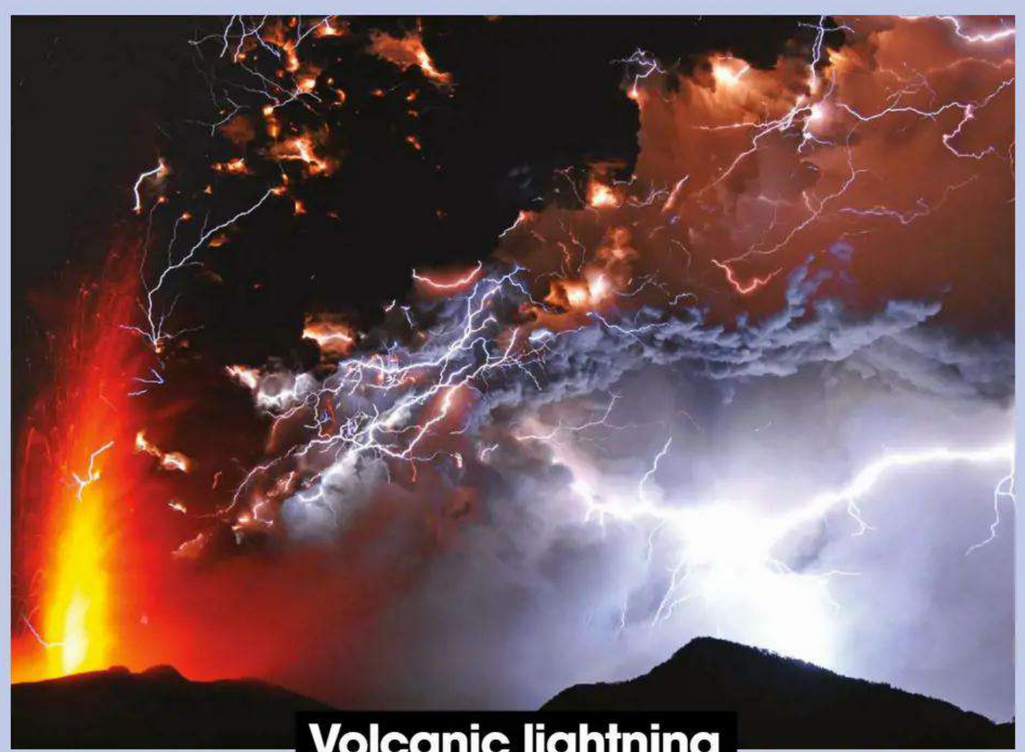
Drastic temperature drops

As air above jet streams is typically colder than average, when streams take a plunge and move south during winter, freezing conditions form in areas now above the air's path.

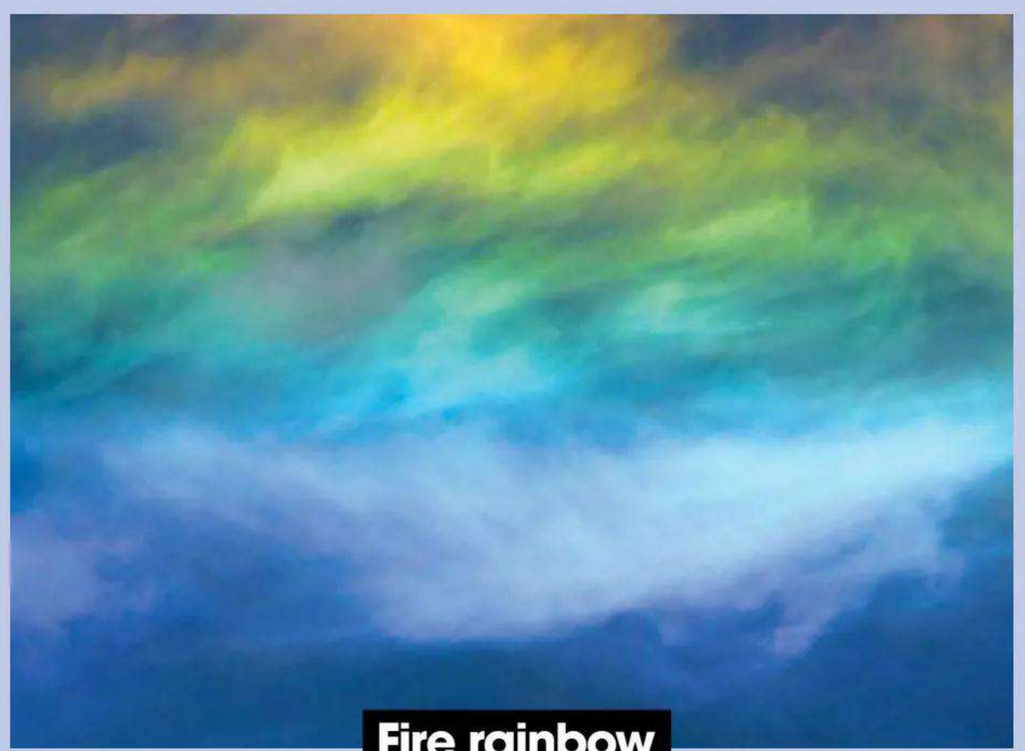
Travelling in jet streams

As well as transporting weather, these highways in the sky can be utilised by aeroplanes to power us towards our destinations. Planes often use the streams as a speedier route, cutting down on air time. Jet streams started to be used for air travel in the early 1950s after a flight from Tokyo to Honolulu cut over six hours off the usually 18-hour journey. Apart from time, an added perk that comes with using these natural currents in aviation is the savings made in fuel consumption. The North Atlantic jet stream holds the most impact on flights during January and February, as this is when the temperature difference between the North Pole and the equator is most drastic.

© Illustration by The Art Agency / Barry Croucher / Getty / San Diego Air & Space Museum Archives



Volcanic lightning



Fire rainbow

World's weirdest weather

The science behind our planet's most spectacular, dangerous and downright bizarre weather phenomena

Have you ever seen a swirling tornado of fire, or heard a sand dune sing? Perhaps you've witnessed balls of lightning floating in the sky or even been caught in a downpour of frogs. Even if you haven't, someone elsewhere in the world definitely has.

Although most of the weather we encounter on a day-to-day basis isn't particularly exciting, it can occasionally deliver some incredibly strange surprises. From enormous hailstones the size of tennis balls to towering clouds of dust that engulf entire cities, weather has the potential to be breathtaking, destructive and even explosive.

The basis for most weather is wind, water and temperature. Thunderstorms are the perfect example, as they involve all three at once. As the Sun heats the Earth, moisture in the air rises up into the cooler regions of the atmosphere via a strong updraft. When it gets high enough, the moisture condenses into water droplets, forming clouds and eventually precipitation. Colder air also sinks in strong downdrafts that create powerful horizontal winds. Thunderstorms are often the main catalyst for some of the world's most extreme weather, spawning lightning, hail and even tornadoes. However, wind, water and temperature can sometimes work in even more unusual ways to create bizarre weather phenomena that scientists are still trying to understand. Most weather, though, no matter how rare and unusual, can be explained by relatively simple science, and over the next few pages we will explore the fascinating processes that cause some of our planet's oddest examples.

Weather key Cloud · Wind · Sun · Heat · Cold · Rain · Lightning · Hail

Huge hail

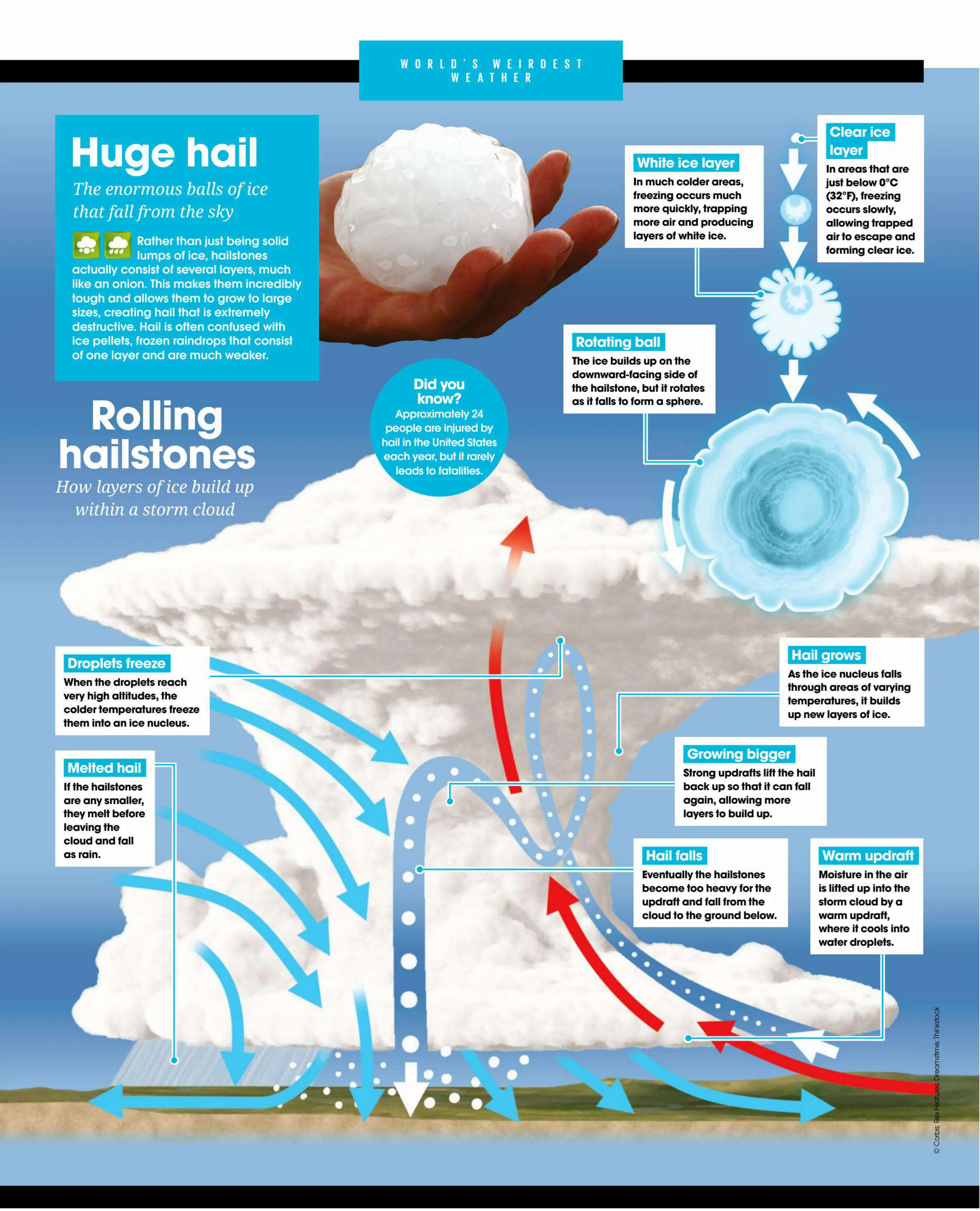
The enormous balls of ice that fall from the sky

Rather than just being solid lumps of ice, hailstones actually consist of several layers, much like an onion. This makes them incredibly tough and allows them to grow to large sizes, creating hail that is extremely destructive. Hail is often confused with ice pellets, frozen raindrops that consist of one layer and are much weaker.

Did you know?
Approximately 24 people are injured by hail in the United States each year, but it rarely leads to fatalities.

Rolling hailstones

How layers of ice build up within a storm cloud



© Corbis; Rex Features; Dreamstime; Thinkstock

Volcanic lightning

The big eruptions that really light up the sky

A volcanic eruption is spectacular and violent enough as it is, but sometimes it is accompanied by big flashes of lightning too. However, this lightning doesn't descend from storm clouds in the sky. It is generated within the ash cloud spewing from the volcano, in a process called charge separation.

Dirty thunderstorm

It is the combination of ice and ash that has lead volcanic lightning to become known as a dirty thunderstorm.

Second phase

It is thought that the later sparks are caused by ice particles higher up in the ash cloud colliding.

Tall plumes

Lightning is considerably more frequent in volcanic plumes greater than 7,010m (23,000ft) in height, because temperatures are colder at higher altitudes.

Normal lightning

Normal lightning is caused by ice particles in storm clouds colliding and separating to create an electric charge.

Did you know?

It's thought volcanic lightning of the Minoan eruption in 1500 BCE inspired Zeus's thunderbolts in Greek myths.

New discoveries

Volcanic lightning was a relatively understudied area of science until 2000, and its cause is still merely speculated.

Ice crystals form

As temperatures are cooler at higher altitudes, the vapour cools and eventually turns into ice crystals, which collide to create lightning.

Difficult to study

Volcanic lightning typically occurs during the beginning stages of an eruption, making it very difficult to record and study.

Initial sparks

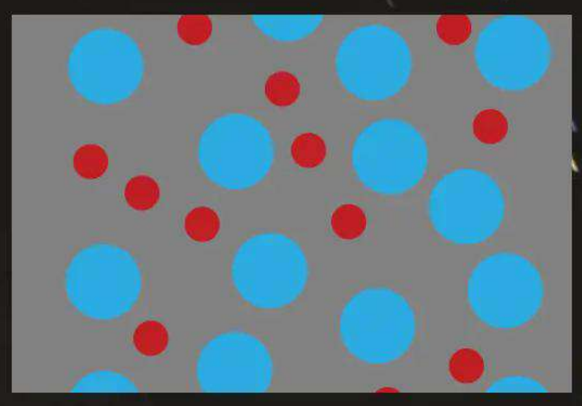
The first sparks of lightning during an eruption are believed to be caused by ash particles colliding as they are ejected.

Water-laden magma

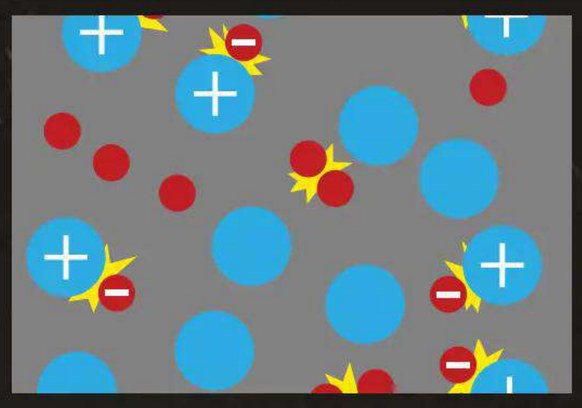
These ice particles form when water dissolved in the magma becomes vapour and rises out of the volcano during an eruption.

> "This lightning doesn't descend from storm clouds in the sky. It is generated within the ash cloud"

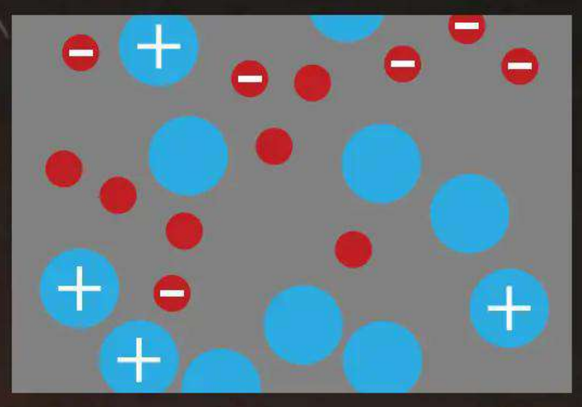
What is charge separation?



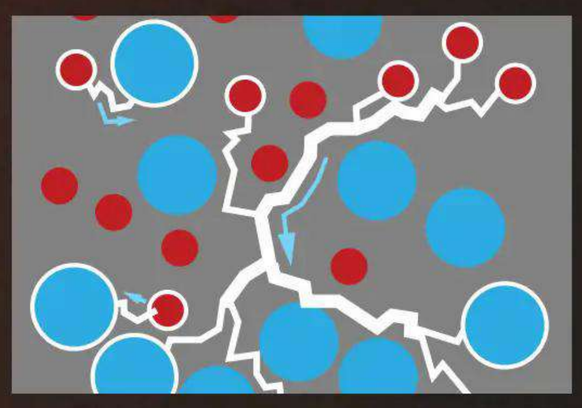
1 The particles within the cloud start out neutral, with an equal number of electrons and protons, meaning that they have neither a positive or negative charge to them.



2 As particles heat up, they collide and transfer electrons in a process known as charge separation. This causes some to become positively charged, and others negatively charged.



3 A difference in the aerodynamics of the positive and negative particles causes them to separate, so some parts of the cloud become more positive, and others become more negative.



4 The electrons flow back towards the positively charged particles when the charge separation gets too great. This forms sparks of electricity and neutralises the particles again.

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Roll clouds

The odd-shaped clouds that roll across the sky

Although they look like horizontal tornadoes, roll clouds are actually completely harmless. Along with shelf clouds, which are more wedged-shaped, they are a type of low horizontal cloud formation, known as an arcus cloud. The difference is that shelf clouds are only created by thunderstorms and remain attached to the main storm cloud, while roll clouds can be formed by a number of different weather systems and are often independent from any other clouds.

They are the result of a mass of cold air meeting a mass of warm air, so can be formed by thunderstorms, cold fronts or sea breezes.

"Roll clouds are a type of low horizontal cloud formation, known as an arcus cloud"

St Elmo's Fire

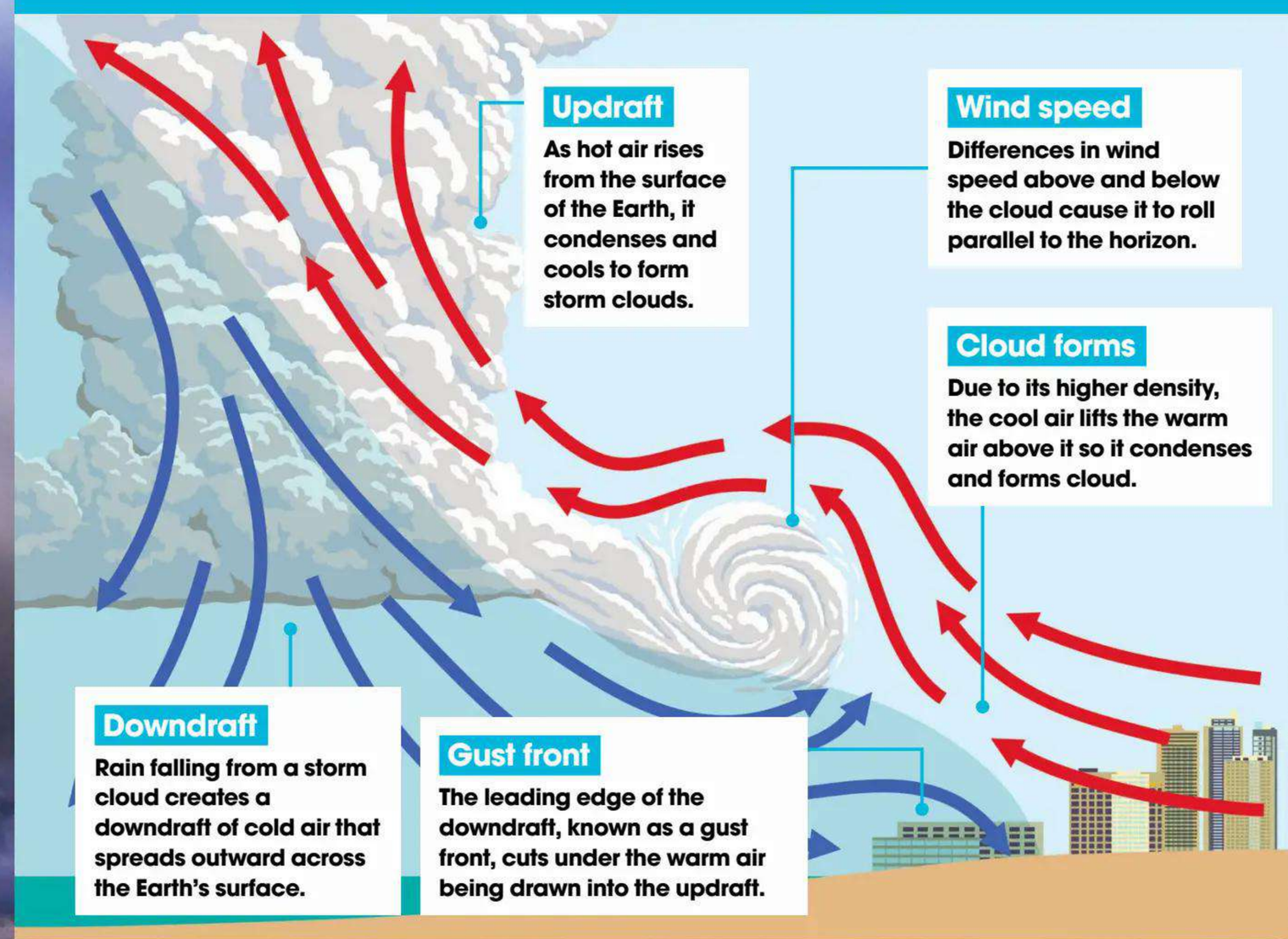
The flames and sparks that climb ship masts and church steeples

Named after St Erasmus, the patron saint of sailors, St Elmo's Fire is the glow of blue flames often observed at the top of tall structures, such as ship masts, in a thunderstorm. It occurs due to charge separation, just like lightning. However, it involves a difference in charge between the air and an object, rather than the air and the ground. It is most common on pointed objects as they discharge electrical energy at a lower voltage level.

Did you know?
Hail can come from any thunderstorm, but large hail is most common in rotating thunderstorms called supercells.

Clouds rolling in

How roll clouds form from a thunderstorm



Rolls clouds can stretch over vast distances and keep rolling for several hours

Fire rainbows

The very rare colourful clouds created by ice crystals and the Sun

Officially known as circumhorizontal arcs, these rare clouds only occur in very specific conditions. Firstly, you must be within 55° north or south of the equator in the summer months.

Then there must also be cirrus clouds, which are thin and wispy and exist at high altitudes where the temperature is very low. Due to their location, these clouds are formed of plate-shaped ice crystals, and when the sun rises to higher than 58°, its rays refract through the crystals, which act like prisms, and split into individual colours to create a rainbow.

Fire rainbows are so called because the wispy clouds look like bright flames licking the sky

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Singing sand dunes

The mountains of sand that can hit the low notes

In several of the world's driest climates, sand dunes regularly emit a strange low-pitched rumbling noise that can be heard from up to ten kilometres (six miles) away. These singing or booming sand dunes baffled scientists for decades, but it is now believed that the sound comes from sand vibrating within the top layer of the dune. This produces a single musical note, typically G, E or F. The thicker the top layer of sand, the lower the note it creates.

Singing in the sand

How dunes create their own tunes

1 Steep slope
The dune must be over 36.5m (120ft) tall with a slope of over 30 degrees in order to create a big enough avalanche.

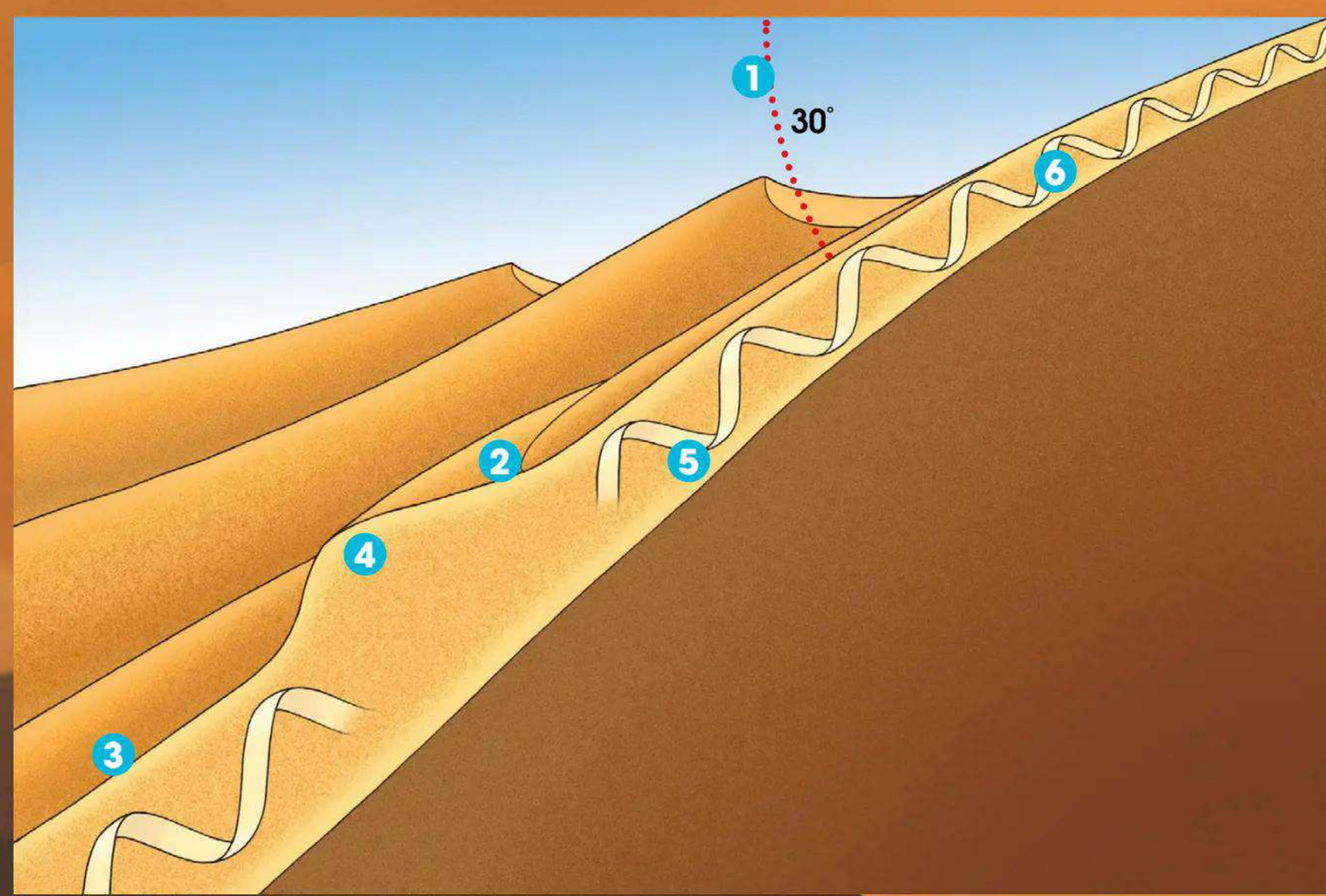
2 Audible sounds
The waves on the surface act like a speaker, converting these vibrations into sound waves and amplifying them.

3 Hot and dry
In order to sing, the sand must be extremely dry so that it can move freely down the dune.

4 Sand avalanche
When wind or human intervention destabilises the crest of the dune, it collapses and triggers an avalanche of sand.

5 Waves of sand
These waves of vibration are trapped within the dry surface layer of the dune, above the wet sand below.

6 Good vibrations
As the grains of sand move, they collide and rub together to create vibrations.



Fallstreak hole

The phenomenon that punches a hole in the clouds

Cirrocumulus and altocumulus clouds are composed of 'supercooled' water droplets that are below freezing temperature, but can't freeze because they don't have any particles around which ice crystals can form. When an aeroplane passes through the cloud, it triggers an expansion of air that causes the surrounding temperature to drop below -40°C (-40°F). This is cold enough to freeze the droplets, which fall as snow and leave behind a hole in the cloud.

These so called 'hole-punch clouds' are the result of extremely localised snowfall

Dust storms

The blizzards of dirt that black out the sky

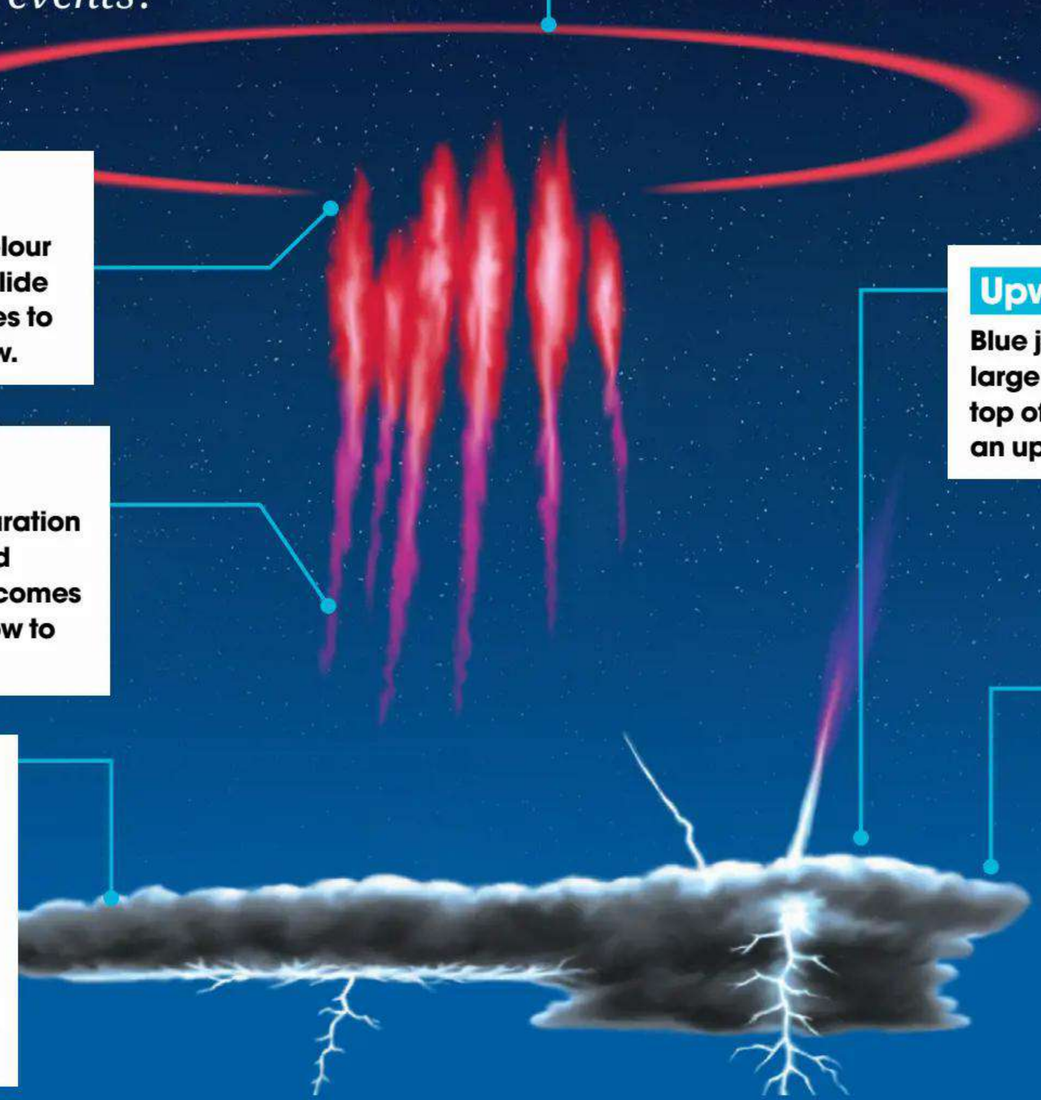
Dust storms are started by gust fronts, the downdrafts of cold air from thunderstorms that hit the ground and spread outward. As the wind passes over the ground, it moves the dust particles and starts a process called saltation. When the particles bounce along to the surface, they start a chain reaction, hitting other particles and causing them to bounce too. As these particles hit each other and the ground, they acquire a negative charge that repels them from the positively charged surface. This lifts them higher, where they get picked up by the wind and blown further.

Dust storms originate in arid or semi-arid regions where the soil is dry and loosely held on the surface

Did you know?
Specific sprites are classified by shape. Carrot sprites, broccoli sprites and jellyfish sprites have all been identified.

Elusive light show

What causes transient luminous events?



Sprites, elves and blue jets

The flashes of light that occur high above storm clouds

As well as the regular lightning that we experience in the troposphere, the lowest layer of the Earth's atmosphere, thunderstorms can also generate further activity much higher up. Transient luminous events (TLEs) are colourful flashes of light that occur in the middle and upper atmosphere and take the form of sprites, elves or jets. As they are very rare and last for just a fraction of a second, these phenomena are usually impossible to see with the naked eye and very difficult to capture on camera and study. Very little is known about them, but high-sensitivity cameras and observations from space are helping scientists to learn more.

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Weather phenomena

How rainbows form

The physics behind these colourful optical illusions

There's always one thing that can brighten up a drizzly day, and that's a rainbow. Arching across the sky, these spectacles of light are formed when moisture in the air interrupts the path of sunlight, splitting it up into all the colours of the spectrum. You might be surprised to discover that raindrops aren't their assumed 'teardrop' shape, but are spherical, an important distinction when it comes to making rainbows.

A raindrop's spherical shape and increased density compared to air provide the conditions needed to bend light to the perfect rainbow-making degree. When sunlight passes through a raindrop, the direction the light is travelling is changed, known as refraction. The light is refracted as it enters the droplet, then internally reflected and sent back out the raindrop in the opposite direction, which is known as the angle of deviation.

When sunlight is refracted, it's broken up into the individual wavelengths of light. The colours range from long wavelengths of red at the top of the rainbow through the seven visible colours in the light spectrum to shorter wavelengths of violet at the bottom. When sunlight is refracted twice in raindrops it creates a double rainbow effect. The double rainbow sits around ten degrees above the primary rainbow and its colours are inverted, with red at the bottom.

Did you know?
A record-breaking rainbow in Taipei lasted almost nine hours.

The size of a rainbow is also determined by the quality of a droplet, known as its refractive index. The refractive index takes into account how well a droplet refracts light when it passes through. The higher the index, the smaller the resulting rainbow. Saltwater, for example, has a high refractive index, which means that rainbows over the ocean are typically smaller than those above freshwater lakes. But why don't we always see rainbows when it rains? Certain environmental and solar conditions need to be met for a rainbow to form. Sunlight has to hit the raindrop at precisely the right angle, which occurs when the Sun is less than 42 degrees above the horizon.

Moonbows

Also known as lunar rainbows, these optical phenomena are created in the same way as their daytime counterparts. In a series of reflections and refractions of light, moonbows form from sunlight that bounces off the surface of the Moon and shines down to Earth's surface as moonlight. Moonlight then passes through rain or mist and is refracted to reveal a rainbow arch. However, moonlight is much weaker than sunlight and doesn't always showcase the full spectrum of colours to the human eye. Instead, we often see a moonbow as an arch of white light.

A moonbow is a spectacular sight

Polar stratospheric clouds above the snow

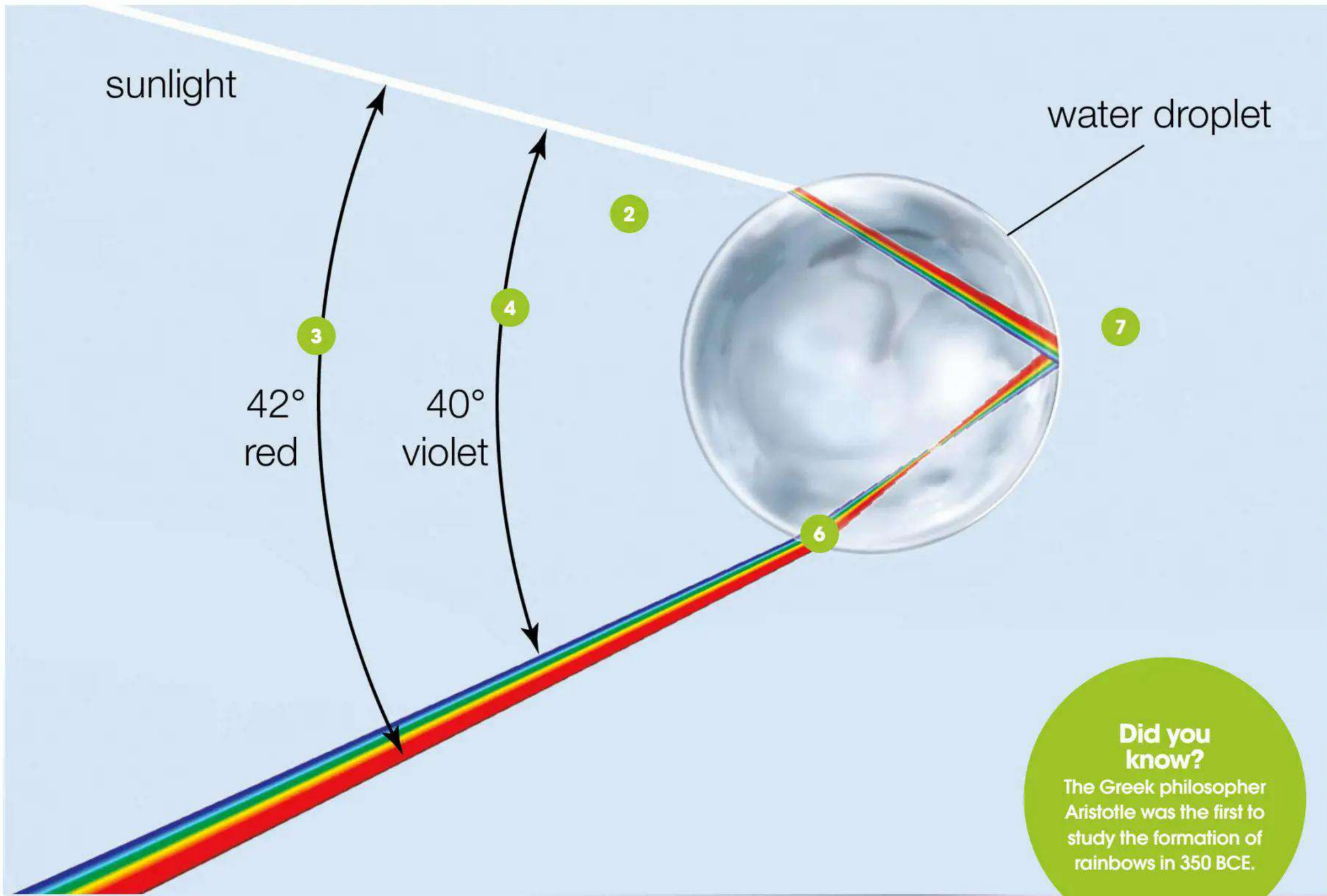
Rainbow clouds

When atmospheric conditions are just right, beautiful polar stratospheric clouds can emerge. This rare phenomenon forms when clouds around 14.5 to 26 kilometres (nine to 16 miles) above the ground at extremely low temperatures are greeted by a rising or setting Sun. When the temperature in the stratosphere reaches below -78 degrees Celsius (-108 degrees Fahrenheit), tiny ice crystals, or 'supercooled droplets', form within clouds. The sunlight that passes through these clouds is scattered into the full array of colours in the visual spectrum.

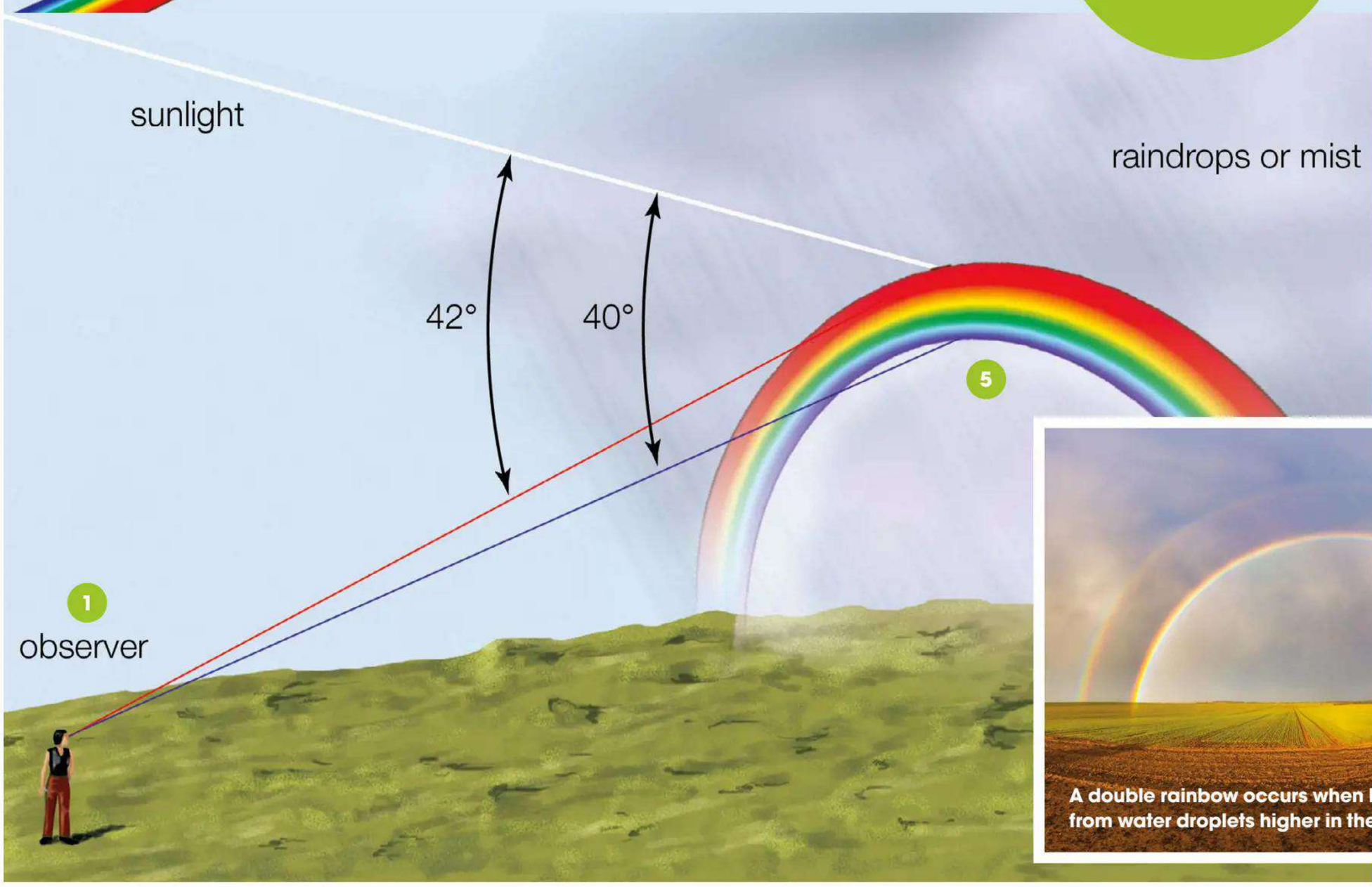
There are two categories of polar stratospheric clouds: Type I and Type II. Type I include ozone-depleting nitric acid, typically producing less rainbow iridescence in the clouds. Type II are much rare than Type I and are made from pure ice, producing a spellbinding 'mother of pearl' rainbow hue.

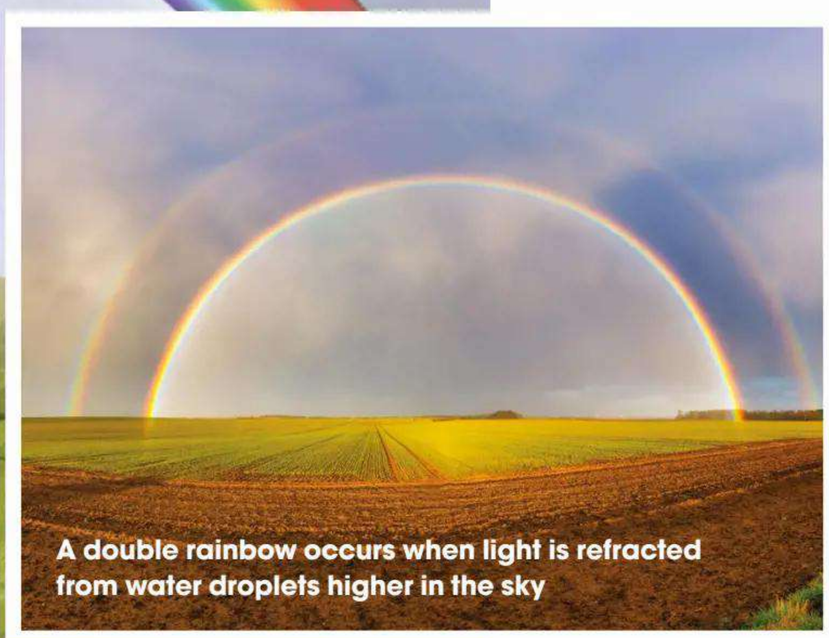
Colours in the sky

How raindrops bend light and shape rainbows



Did you know?
The Greek philosopher Aristotle was the first to study the formation of rainbows in 350 BCE.




A double rainbow occurs when light is refracted from water droplets higher in the sky

1 Light source
To see a rainbow, the Sun needs to be behind the viewer.

2 Water source
Rainbows are formed by water droplets in rain, fog or mist.

3 Red
Red wavelengths of light emerge from a raindrop at 42 degrees.

4 Violet
Violet wavelengths of light emerge from a raindrop at 40 degrees.

5 Placing colours
Due to the different angles colours emerge from a raindrop, rainbows have blue hues on the inside of the arc and red on the outside.

6 Seven colours
The seven colours of the rainbow are arranged into wavelengths of light, starting with the longest, red, to the shortest, violet.

7 Internal reflection
A water droplet is denser than air. When light passes through, it causes the light to change direction.

© Alamy / Getty

Double, or multiple, rainbows are only visible to the naked eye when the incoming sunlight is unhindered by atmospheric effects, so is very intense

Did you know?
The dark band between double rainbows is named after Alexander of Aphrodisias who mentions it in 200 CE.

Double rainbows

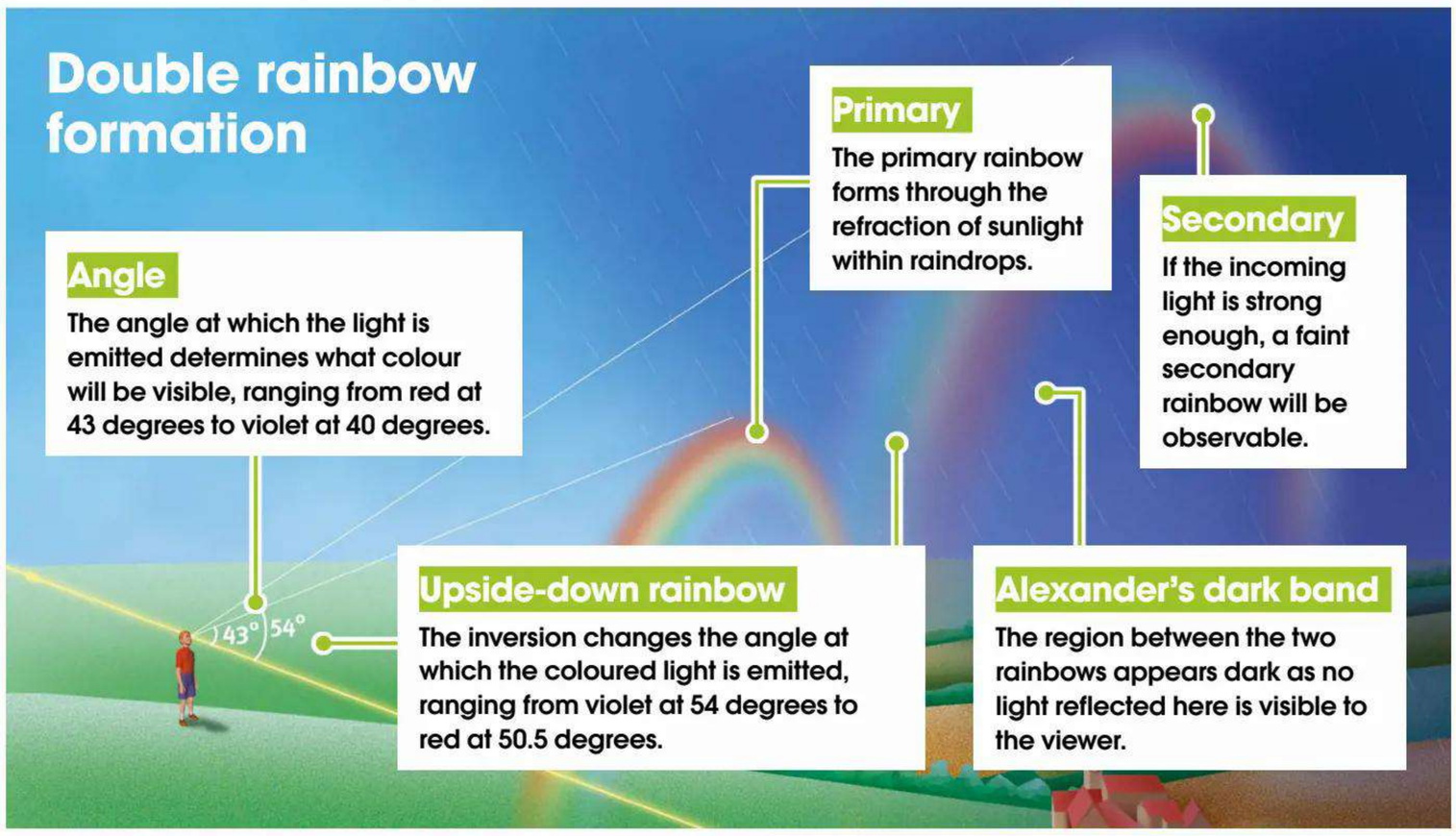
What causes this colourful meteorological phenomenon?

Regular rainbows occur when moisture in the air – commonly rain, but also mist or spray from a waterfall – refracts sunlight in such a way that it is broken up into its constituent colours.

The phenomenon occurs when the Sun is positioned behind you and sunlight passes through the airborne water. The light refracts (bends) inside the droplets and the white light is broken up. Each colour has a different wavelength so, depending on the angle of refraction, a different colour of light will be reflected outwards; the result of this process is what we observe when we see a rainbow.

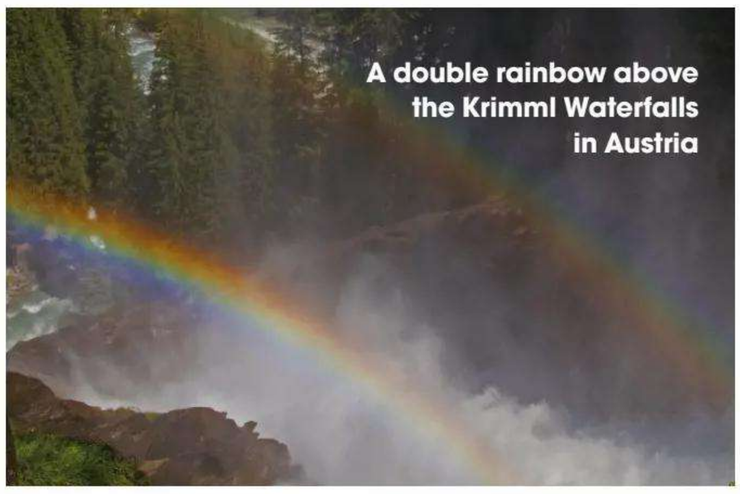
Every rainbow is accompanied by another, secondary rainbow, but it's usually too dim to see. This double rainbow effect is due to the continued reflection of light inside each water drop. Sunlight is actually reflected twice inside a drop: once to produce the primary rainbow and a second time at the back of the drop. This second reflection inverts the light but undergoes the same refraction, so exits in the same way as before – though upside down.

This second reflection reduces the intensity of the sunlight, but it also produces a second inverted rainbow, creating a double arc of multicoloured light in the sky. Interestingly, sunlight can reflect many more times inside a water drop so many more rainbows can be produced, but the incoming light is rarely strong enough for these to be visible to the naked eye.



© SPL

"Every rainbow is accompanied by another secondary one, but it's usually too dim to see"



A double rainbow above the Krimml Waterfalls in Austria

Unlike earthquakes, frost quakes rarely cause significant damage

Did you know?
Frost quakes can cause damage, but not on the same scale as an earthquake, these icy tremors release far less energy.

Frost quakes

What causes these seismic events that shake the ground and create a loud boom?

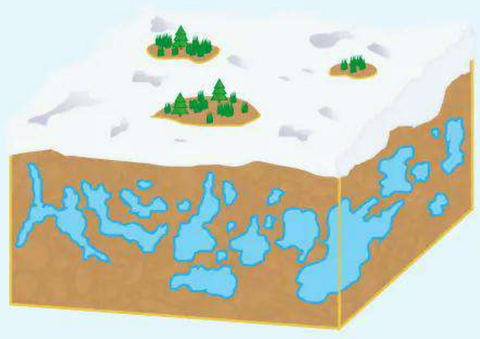
A frost quake, or ice quake (scientifically known as a cryoseism) is a rare, natural phenomenon that makes the ground shake in the immediate proximity of its epicentre and produces a loud booming sound. These kinds of tremors are very similar to earthquakes, but the meteorological and geological conditions at work make them very distinct events.

Frost quakes occur in areas susceptible to cold air masses. Usually there is some snow covering on the ground, but only around 15 centimetres (6 inches) – not enough to insulate the ground. For a frost quake to happen, the ground must become saturated, which could occur after heavy rain or from a thawing of ice or snow. When such a large quantity of water seeps down into the soil or bedrock, the ground inevitably becomes very wet. If this is followed by a rapid drop in temperature, a deep freezing of the ground occurs, resulting in the underground water freezing as well.

Water expands as it freezes, which in the case of the underground moisture puts enormous stress on its surroundings. As this pressure increases, a buildup of explosive stress is finally relieved in the form of a frost quake. A loud rumbling can be heard as the ground shakes and cracks, and tremors can be felt nearby.

Cryoseismic booms

The step-by-step formation of a cold quake



STEP 1

Water becomes trapped
When water seeps into soil and bedrock after a heavy downpour of rain, it becomes trapped underground. Water can also become trapped underground when ice or snow begins to thaw, trickling down into the soil and bedrock.

STEP 2

The water freezes
In cold-weather months when temperatures plummet, the saturated ground rapidly freezes. This sudden, deep freezing of the ground not only results in frozen soil and rock, but the water beneath the surface also turns to ice.

STEP 3

Pressure builds
The freezing water begins to expand underground, consequently putting more and more pressure on the soil and bedrock that surrounds it. As explosive stress builds, fractures in the rock occur.

STEP 4

The soil cracks
When the explosive stress is finally relieved, a loud bang can be heard, similar to an explosion or gunfire. Shaking vibrations, much like those that occur during an earthquake, can also sometimes be felt on nearby land.

© Alamy; Illustration by Alex Phoenix

What is freezing rain?

Discover the supercooled droplets that can be very dangerous

Freezing rain usually begins as snow, ice, sleet or hail. When it passes through a layer of warmer air, it melts and turns back into a liquid. However, if the rain travels through a shallow layer of cold air – with a temperature below freezing – as it continues to fall, this supercools the water droplets. When these droplets hit an object, such as a road, vehicle or tree, they freeze on impact. This can create dangerous driving conditions, and the weight of ice on power lines or trees can cause them to collapse.

While freezing rain is more common in the US, it is a rare occurrence in the UK, as conditions have to be so precise. The sub-freezing layer must be relatively shallow, at 600 metres (1,969 feet) above the surface.

An accumulation of freezing rain can add weight to trees and power lines, causing serious damage

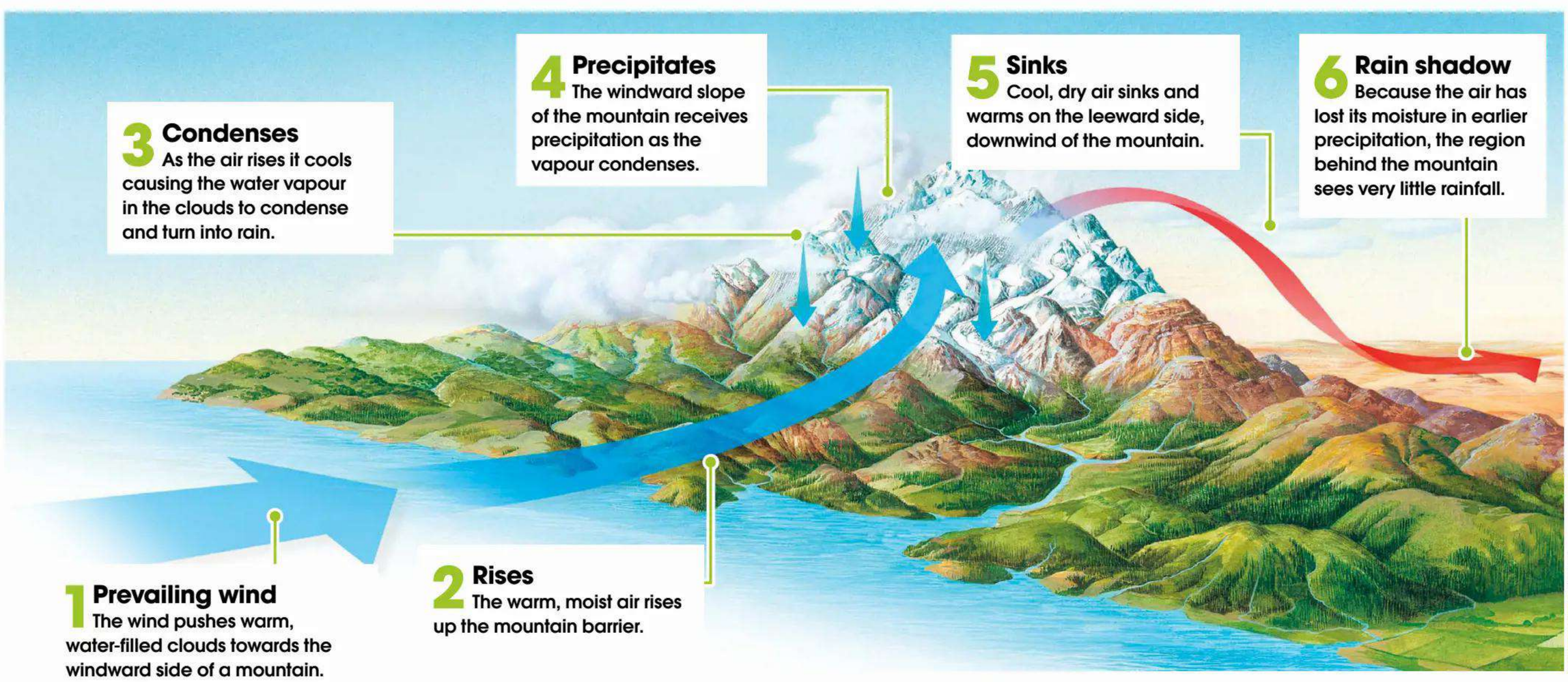
Rain shadows

Why does this weather phenomenon cause deserts to form on one side of a mountain?

A rain shadow is an area that receives very little precipitation due to a substantial obstruction, most commonly a large mountain.

Such an obstruction blocks the path of moisture-rich rain clouds. Due to a process of cooling and condensation, a shadow area of dry conditions is likely to develop beyond this barrier.

Essentially this means that the windward side of a mountain receives plenty of precipitation whereas the leeward side might be left extremely dry. This can result in a dramatic contrast of conditions with the formation of a desert on one side but not the other. The warm, dry breeze that blows down the leeward side of a slope is known as a foehn wind.



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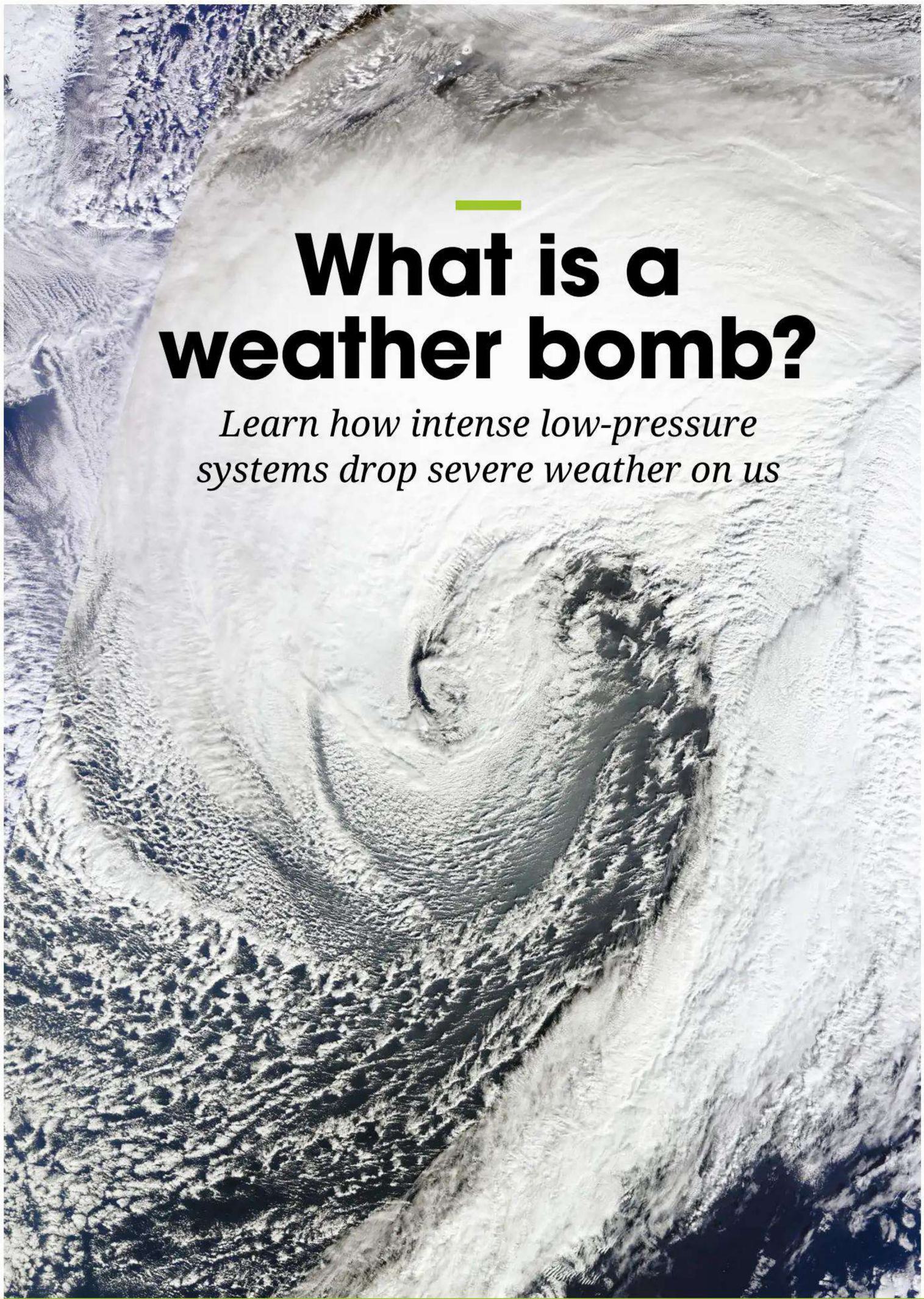
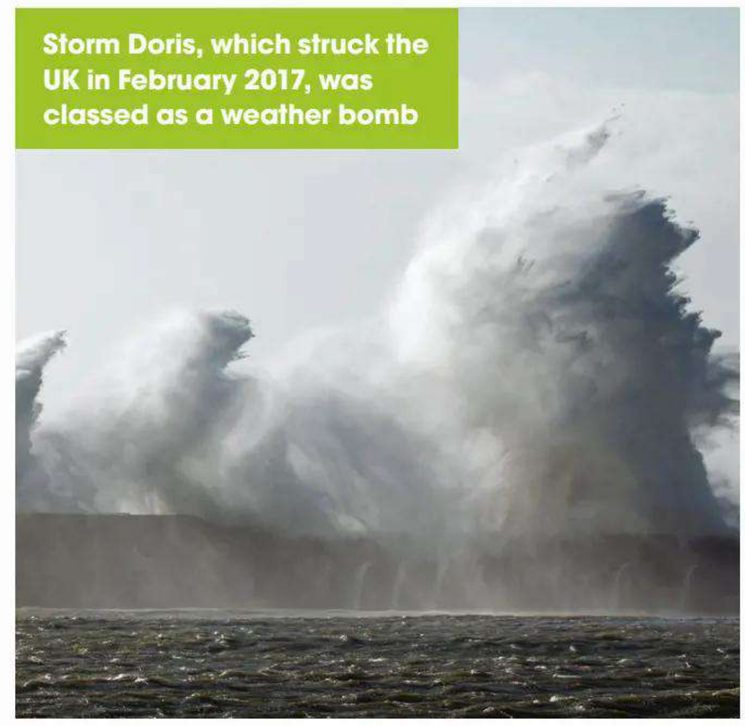
What is a weather bomb?

Learn how intense low-pressure systems drop severe weather on us





Storm Doris, which struck the UK in February 2017, was classed as a weather bomb

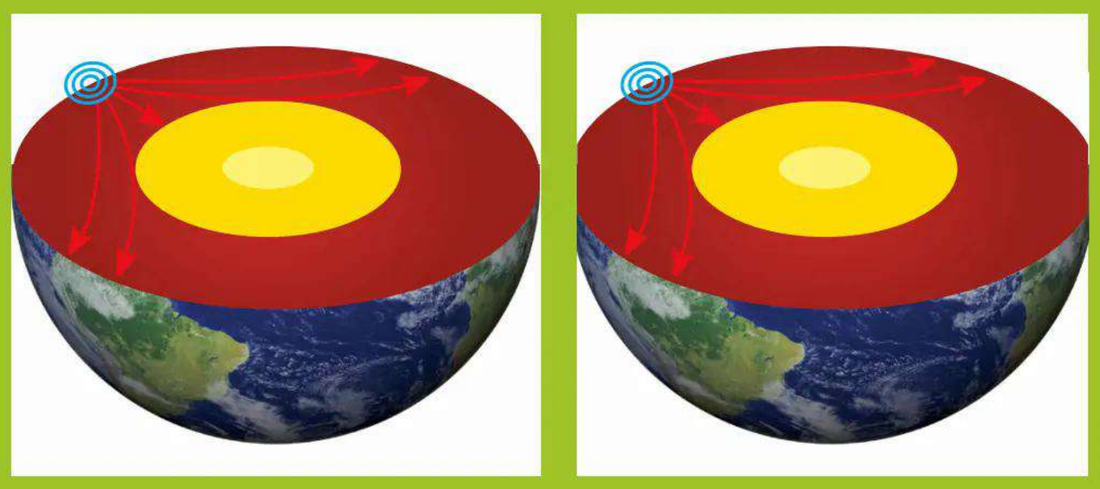
When a storm hits, meteorologists may refer to it as a weather bomb, but this isn't just a dramatic name given to all severe weather events. A weather bomb is in fact the unofficial term used to describe a particular type of low-pressure system that can result in damaging gusts of wind.

Low-pressure systems occur regularly across the planet and are caused by warm air rising from the Earth's surface. They generally lead to unsettled weather conditions, as when air rises, it cools, causing water vapour to condense and form clouds. However, when an area of low pressure passes beneath a powerful jet stream of rapidly moving air high up in the atmosphere, it develops into something much more intense. The jet stream removes air from the column of low pressure, reducing its weight so that the pressure at sea level falls even further. If the pressure drops by 24 millibars (2,400Pa) or more over a 24-hour period this is described as explosive cyclogenesis, which is the official name for a weather bomb.

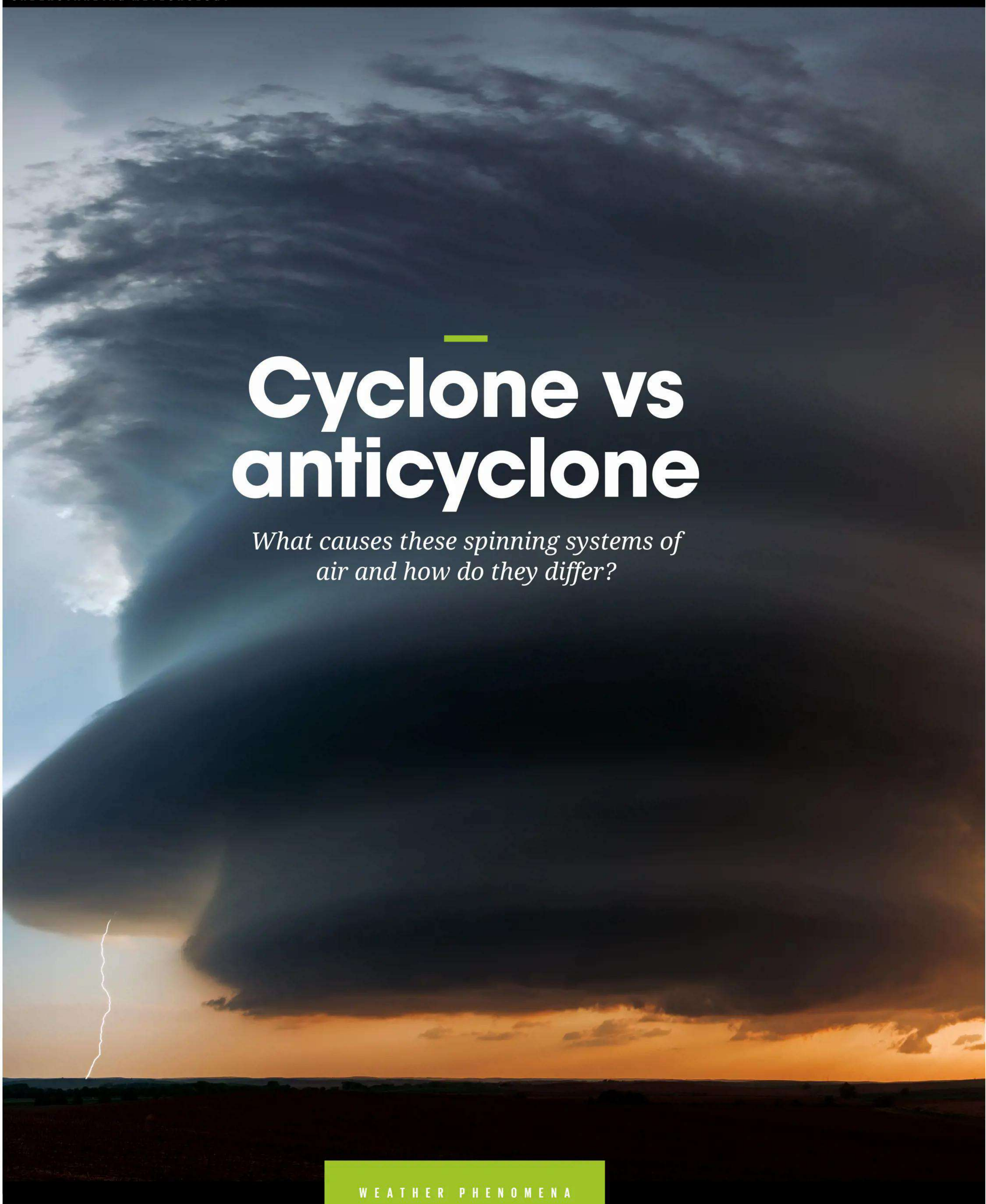
As the falling pressure sucks in more air, the column begins to rotate faster and faster, resulting in strong winds that peak over a period of a few hours. These winds can be powerful enough to blow down trees and cause structural damage, putting members of the public at risk.

Tiny tremors

Storms – including weather bombs – that happen at sea send tiny vibrations known as microseisms through the Earth. This occurs when waves crash together, sending energy into the ocean floor and beyond. The tremors are more subtle versions of those caused by earthquakes, and fall into two categories: pressure waves, or 'P' waves, squeeze and expand the rock, while slower transverse waves, or 'S' waves, wobble the rock from side to side. The P waves are routinely picked up by scientists on the opposite side of the world to their source, but S waves are more illusive. However, in 2014, seismologists in Japan were able to track the source of these slow-moving S waves for the first time, tracing them back to a weather bomb off the coast of Greenland. Researchers hope this breakthrough will open up a new way to study Earth's interior.



Studying tremors that travel through the planet can help scientists better understand Earth's structure



Cyclone vs anticyclone

What causes these spinning systems of air and how do they differ?

"Anticyclones are associated with summer weather and dry winter days"

LEFT
A mesocyclone moves through Nebraska's Great Plains

BELOW
Anticyclones have periods of calm weather that can last a few days

Cyclones and anticyclones are generated when areas of high and low air pressure collide. These are created by differences in temperature and humidity.

Air temperature affects the molecules' kinetic energy. The higher the temperature, the more the molecules move and collide. Humidity, on the other hand, affects the air itself. The atmosphere's main constituents – diatomic oxygen and nitrogen – are heavy compared to water vapour. The water in humid air replaces some of the heavier molecules, making it lighter than dry air, and therefore of a lower pressure.

An anticyclone is a region of high atmospheric pressure. The air descends through the system, spreading out sideways as it makes contact with the ground. The compressed air causes a rise in temperature – hence why anticyclones are associated with summer weather and dry winter days.

In contrast, a cyclone is centred around a region of low pressure. Inward spinning winds draw air upwards into the system – as it rises, water vapour cools and condenses, resulting in cloudy weather and storms.

Tropical cyclones

The name for a storm system with rotation, high winds and heavy rains depends on its intensity and the region in which it forms. The mildest form is the tropical depression, with sustained winds of up to 60 kilometres per hour (37 miles per hour) and rain but no cloud rotation. Next is the tropical storm, which has winds of up to 117 kilometres per hour (73 miles per hour) and a circular shape with rotation.

The strongest storm has winds of at least 119 kilometres per hour (74 miles per hour), and a distinctive eye – an area of calm and extreme low pressure. It might be known as a hurricane, a tropical cyclonic storm, a tropical cyclone or a typhoon. They're only called typhoons, for example, when they form in the Northwest Pacific Ocean, while storms that develop in the Northeast Pacific and North Atlantic are hurricanes. It's rare for these storms to be killers, but when they are, they do it big – usually in the forms of flooding, mudslides or diseases after the event.

© Getty

What is El Niño?

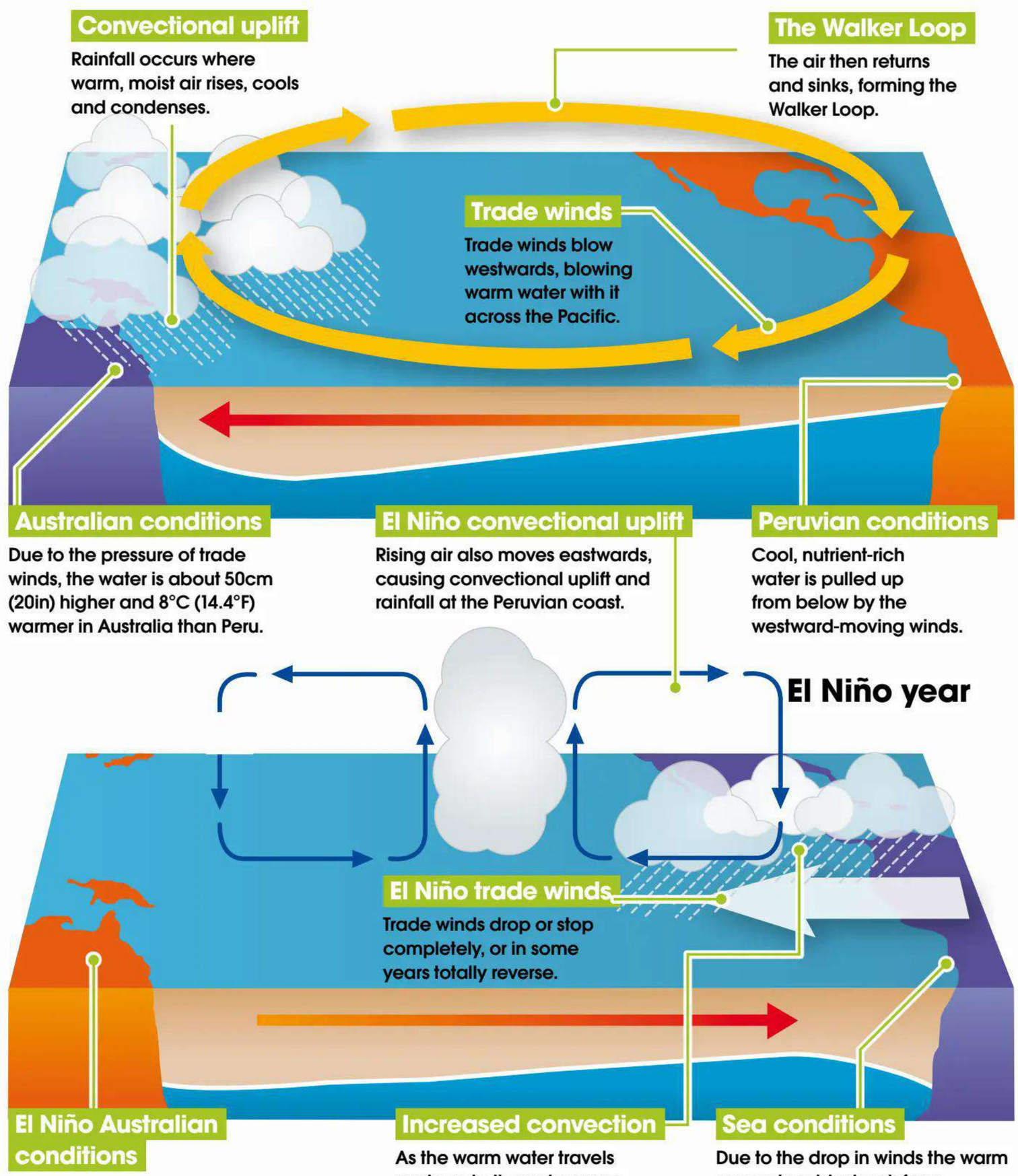
The weather-altering phenomenon unveiled

El Niño is the presence of warm surface water along the western coasts of South America (especially Peru), due to an altering of normal winds in the Southern Hemisphere. In an El Niño year, the trade winds that blow towards Australia either greatly reduce, die completely, or in extreme years even reverse. This stops the ocean current from pushing warm water towards Australia, and instead the higher waters on the Australian coast ebb back towards Peru. This increases both the sea temperature and level on the south American coast. The changes in the area also mean that the convectional uplift and resulting rainfall which normally occurs in Australia moves to the Peruvian coast.

Scientists still struggle to fully understand El Niño, when it is coming and why it occurs. Each one is different and how the atmosphere reacts each time varies. Due to these varying conditions and irregularity, the cause of El Niño is not completely understood. While we know it is caused by wind change, little more is certain.

El Niño occurs roughly every four to seven years and lasts on average between 12 and 18 months. However, in recent years it appears to be increasing in regularity. Closely linked with the El Niño phenomenon is that of La Niña. In La Niña years normal conditions of the Pacific are heightened, due to extra strong trade winds. This means the waters of Peru are much colder than normal, and the convectional rain of eastern Australia is heavier.

El Niño vs normal



El Niño by satellite

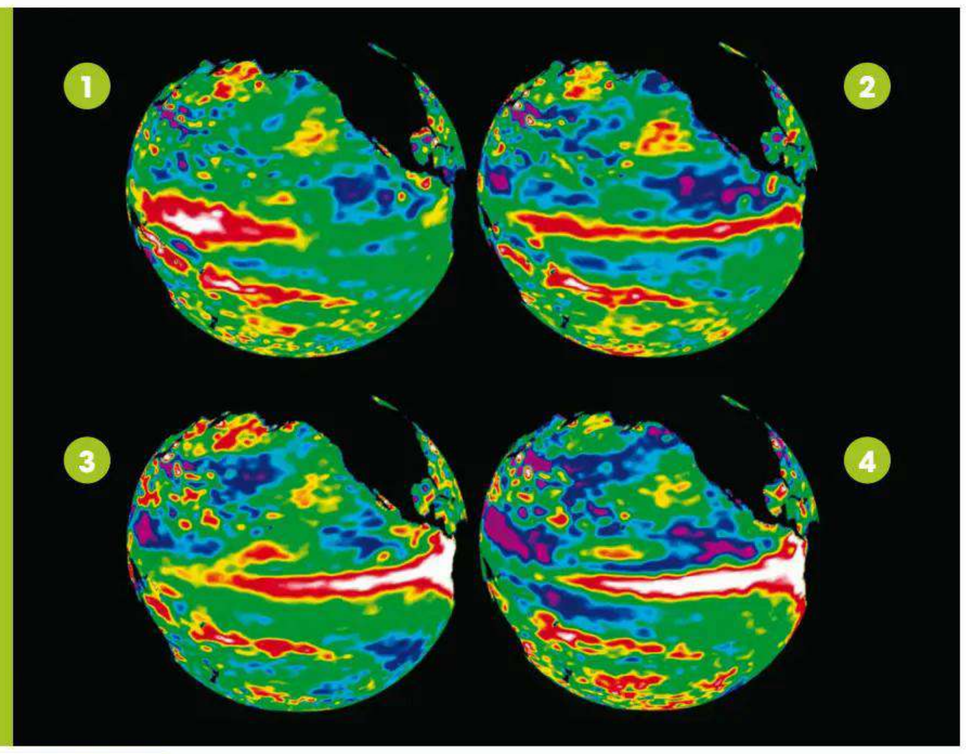
These satellite images show sea height during El Niño in 1997

1 The beginning
The sea level is high off the coast of Australia, as you can see by the red and white. The sea level is low off the coast of Peru, as demonstrated by the blue.

2 On the move
The water across the Pacific becomes deeper, as the water from the Australian coast begins to travel eastwards towards Peru with the dying down of the trade winds. This is shown by the red strip.

3 The main event
This diagram shows El Niño at its height. The sea at the Peruvian coast is far deeper than normal now the water has made its way across from Australia. Blue can be seen near the Australian coast, where the sea level is shallower.

4 On its way back
As the trade winds begin to pick up again, the water moves back from the Peruvian coast to its rightful place on the Australian coast. This is shown by the red strip beginning to ebb westwards.



La Niña explained

How this Pacific Ocean phenomenon is responsible for weather extremes

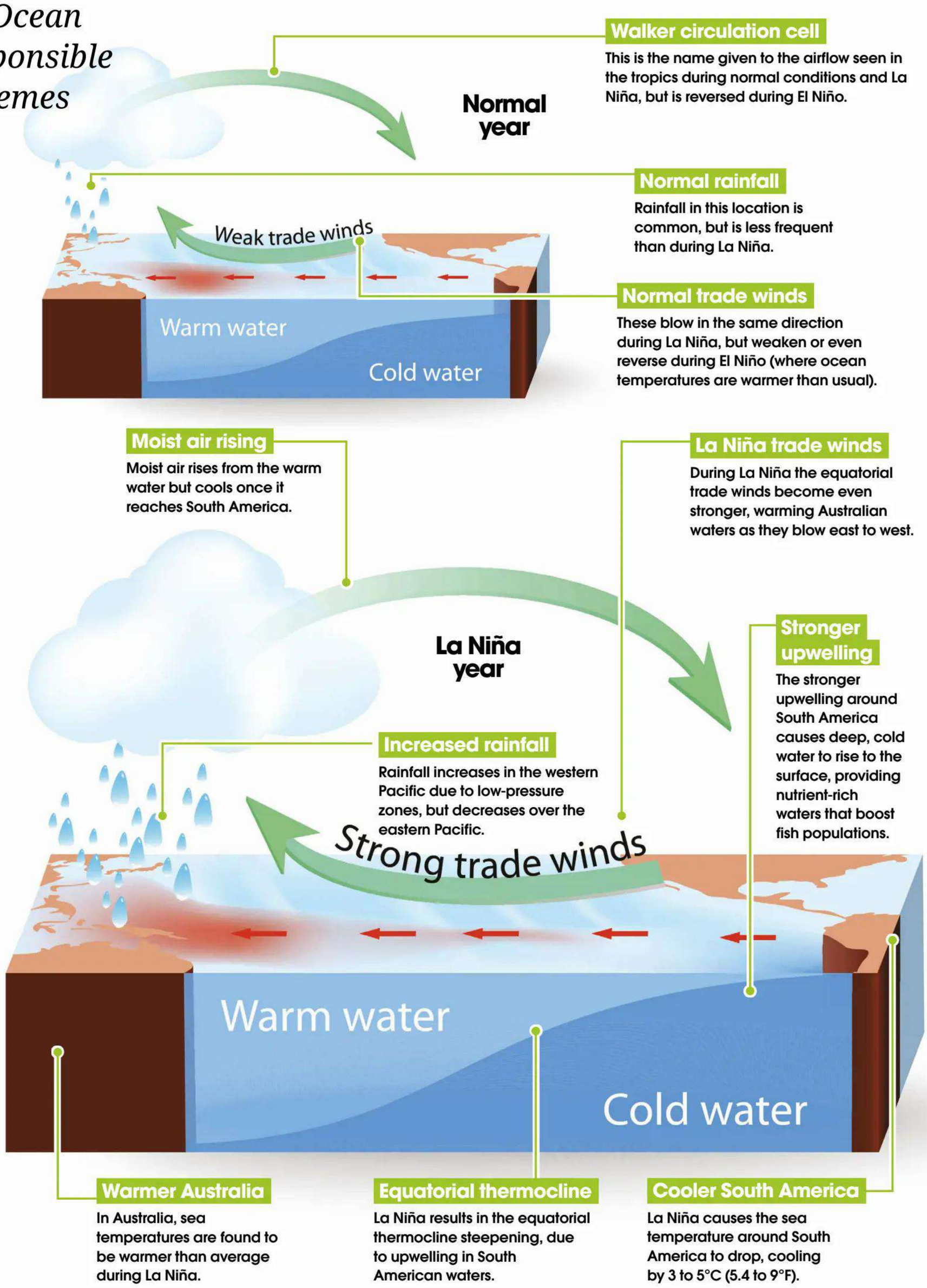
La Niña is defined by unusually cold ocean temperatures in the equatorial Pacific. It's caused by a build-up of very cool water in the tropical Pacific, which is brought to the surface by easterly trade winds and ocean currents. This upsurge of water causes sea-surface temperatures in areas near South America to drop drastically.

La Niña can trigger changes in rainfall patterns, atmospheric circulation and atmospheric pressure, having dramatic effects on the global climate. La Niña events are associated with cataclysmic flooding in Northern Australia. In 2010, they resulted in arguably the worst flooding in Queensland's history, causing more than two billion Australian dollars' worth of damage and requiring the evacuation of over 10,000 people. La Niña does have some positive effects, however, often boosting the South American fishing industry due to the upwelling of nutrient-rich waters, where fish populations thrive.

Although our understanding of La Niña has grown, forecasting it is still difficult, even when combining the latest satellite and marine buoy data. With such a global impact, every effort is being made to find a way to predict this age-old phenomenon.

What happens during La Niña?

See how a period of cooler sea temperature can have far-reaching effects



Clouds that shine at night

How do these glow-in-the-dark noctilucent clouds form high in the Earth's atmosphere?

How noctilucent clouds form

Observing
The light from the Sun that hasn't been scattered by the ice crystals reflects into our eyes, illuminating the noctilucent clouds.

Did you know?
The biggest cloud is the cumulonimbus. They're dark and can contain millions of tons of water.

Scattering
After dusk, sunlight can still reach the mesophere - the coldest part of Earth's atmosphere. The light hits ice crystal shards and is scattered, with the stratosphere absorbing red light, leaving only blue.

Nucleus
These ice crystals need to contain some kind of nucleus to effectively scatter the light. This could be either meteorite or volcanic dust.

Temperature
Ice crystal shards form when the temperature of the mesophere falls below -120°C (-184°F), but this only happens in the months either side of the summer solstice.

Sun sets
Once the Sun is more than six degrees below the horizon from the perspective of the viewer, it sends sunlight up into the mesosphere, 80km (50mi) up.

What are snow doughnuts?

Snow doughnuts, or rollers, are a rare natural phenomenon. If snow falls in a clump, gravity can pull it down over itself as it rolls. Normally it would collapse, but sometimes a hole forms. Wind and temperature also play key roles.

Raining animals

The very real threat of amphibious rain

Although there are no accounts of it actually raining cats and dogs, other animals, such and fish and frogs, have been seen to fall from the sky in some parts of the world. This occurs when waterspouts – small tornadoes that form over water – suck up low-weight items, such as small creatures, with their low-pressure core. When these waterspouts hit land, they lose some of their energy and slow down, releasing whatever it is that they are carrying. Their spinning winds can reach up to 480 kilometres per hour (300 miles per hour), helping them to suck up objects from up to one metre (three feet) below the surface.

Ball lightning could be the result of superheated earth entering the atmosphere

The mystery of ball lightning

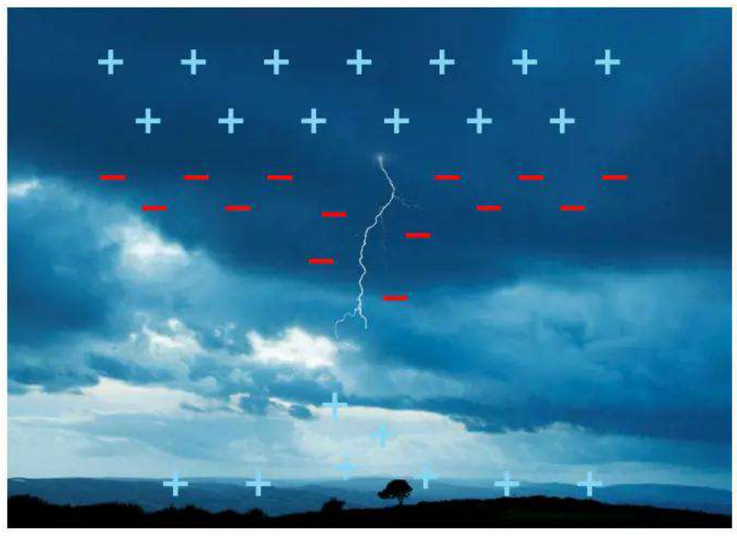
What's the most plausible explanation for this rare atmospheric phenomenon?

It's a weather phenomenon that has puzzled the minds of scientists for thousands of years. As far back as the ancient Greeks, there have been eyewitness accounts of floating, glowing balls of electricity emerging after a thunderstorm. These balls of energy have ranged from the size of a golf ball to a few metres/feet wide. There have even been reports of the plasma-like balls floating in the sky and entering people's homes before vanishing.

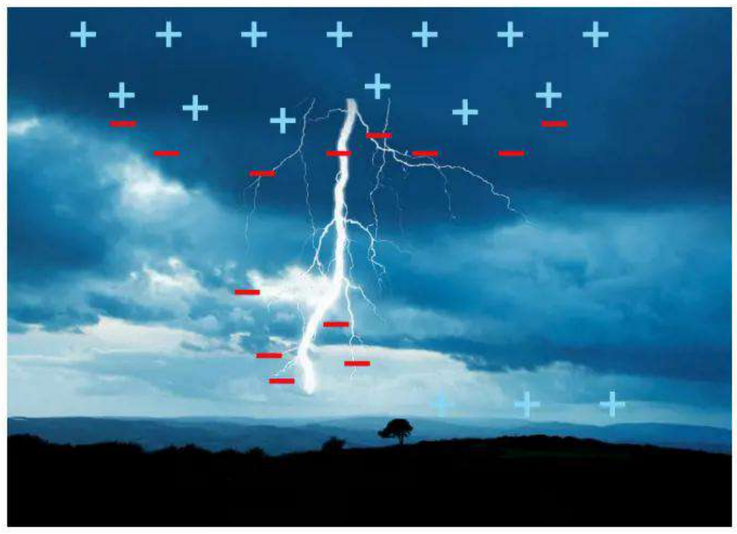
Explanations for these electrical oddities vary, but one of the only theories to be proven in a laboratory is the theory of vaporised silicon. In the ground, soil and sand have high quantities of silicon dioxide. When this compound is heated by the energy emitted by lightning it creates balls of light, which could explain ball lightning sightings in nature. However, this does not account for the witness reports of ball lightning passing through windows and entering a building before dissipating.

There may not be a one-size-fits-all answer when it comes to explaining ball lightning. It is possible that there are many different types of this phenomenon, each caused by a different process. The main hurdle for researchers is the infrequency of ball lightning events, making them difficult to study.

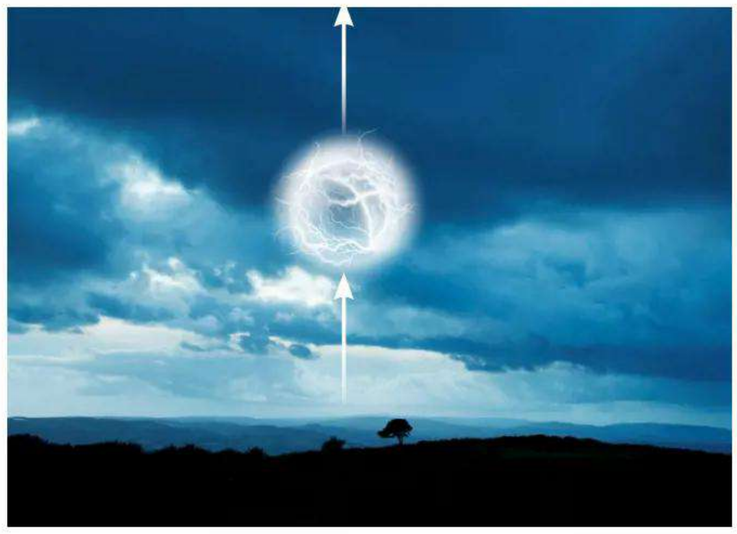
1 Cloud batteries
When large clouds are formed in the air, charged water particles separate. The positively charged particles move to the top of the cloud and the negative particles fall to the bottom.



2 Generating a connection
The ground is positively charged and attracts the negative charge at the cloud's base. A channel of ionised air forms from the cloud down and ground up. When they meet, they create an electric connection.



3 Unleashing lightning
When a connection between the ground and the cloud forms lightning strikes, heating the air to 30,000°C (54,023°F), five times the Sun's surface temperature.



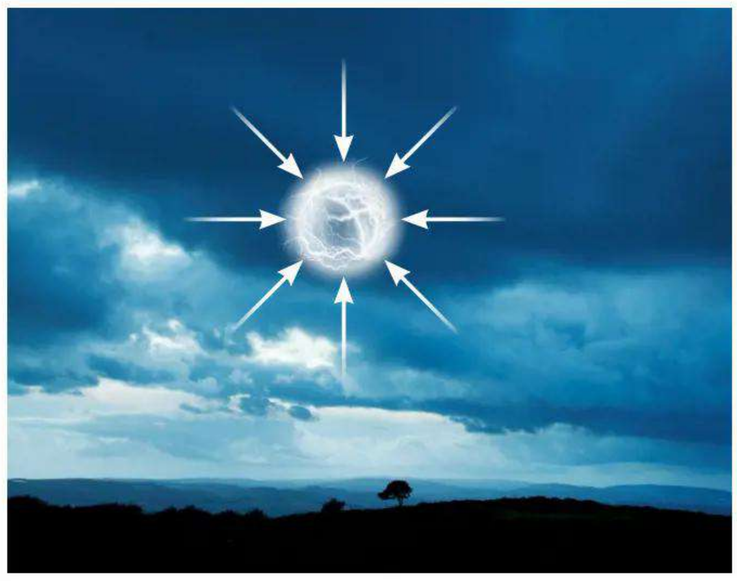
4 Stripping silicon
This extreme temperature strips oxygen from the silicon dioxide in sand and soil on the ground and superheats the vaporised silicon into a gas bubble.

Is it all in your head?

Some studies have concluded that ball lightning sightings are the result of magnetic field-induced hallucinations. During a thunderstorm, strong magnetic fields are created that can stimulate the brain's visual cortex. In studies using a transcranial magnetic stimulator – a non-invasive machine that delivers targeted magnetic fields into the brain – it was found that test subjects saw moving lights reminiscent of ball lightning reports. However, the range of colours sighted in the field, including blue, green and orange, vary more, whereas study participants only see white or grey light. Hallucinations are just one of many theories, but the mystery of ball lightning may be the collective effect of many different factors.

Source: Wiki / Binadot

Many people have claimed to have witnessed balls of light travelling into their homes



© Getty Images, Alamy

5 Forming bright light
As it cools and recombines with atmospheric oxygen the process generates energy and emits light, appearing as a ball of lightning.

Nature's light shows

Discover the atmospheric conditions that can help create some of the most spectacular illuminations on Earth

Auroras

In space, charged ion and electron particles are constantly escaping from the Sun's gravitational field and travelling towards Earth at high speed. Most of them bounce off the Earth's magnetic field, but some are funnelled through its weak spots by the North and South Poles. They then collide with oxygen and nitrogen atoms in the Earth's atmosphere, causing them to give off particles of light called photons. Depending on where the collision takes place in the atmosphere, these photons appear as different colours. For the best chance of seeing this meteorological phenomenon, check the weather forecast for strong solar activity and clear, cold skies.

Lightning

Collisions between water droplets and particles of ice in storm clouds create a strong electric field, which separates atoms into positively charged protons towards the top of the cloud and negatively charged electrons towards the bottom. Eventually the charge builds up so much that electrons shoot towards the protons within the cloud or towards the positively charged ground in a flash of lightning, one of Earth's most breathtaking light displays.

Bioluminescent phytoplankton

Various species of phytoplankton produce light, but the most common are dinoflagellates. Movement of predators within the water likely starts a chemical reaction, which causes a protein called luciferin to produce a bright blue light. This is thought to act as a form of defence against predators. To catch this incredible light look out for calm, dark, warm skies as phytoplankton blooms are found in warm water with no wind.

Light pillars

During the day time, flat ice crystals in the upper atmosphere can sometimes reflect the light from the Sun, creating a 'Sun pillar'. However, when temperatures are below zero, these ice crystals can sometimes form nearer to the ground. There they can reflect light from streetlights and houses to create light pillars, which can happen at any time of the day.

Fireflies

The cells inside a firefly's abdomen contain the chemicals luciferin and adenosine triphosphate, as well as the enzyme luciferase. When these ingredients mix with oxygen, which is supplied to the cells through a tube in the insect's abdomen, they emit light. Either by nerve cells or by controlling the flow of oxygen, the bug can turn the light on and off in quick bursts. In young firefly larvae, this light warns predators that the insect may contain toxic chemicals, while in adults it is used for selecting a mate. For the strongest glow, wait for warm, humid nights when fireflies are most active.

Did you know?
Bioluminescence has evolved separately at least 50 times in a range of species, including fungi.

Glow worms

Glow worms are actually bioluminescent beetles, and they produce light in the same way that fireflies do. Only adult females of the species glow, as they use their light to attract flying males for mating. Spot them in warm, low-lit skies and light rain.

Extreme weather

Record-breaking weather

Discover where and when the elements have been at their most extreme

"Within 30 minutes the El Reno tornado was moving at 80kph (50mph)"

EXTREME WEATHER

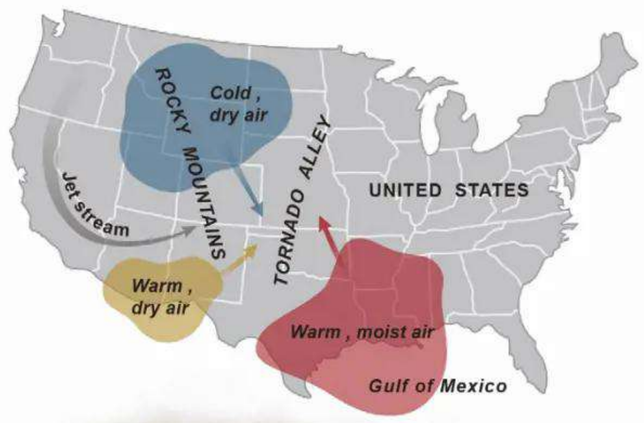
Widest tornado

The classic tornado is funnel-shaped with a narrow bottom, but this isn't always the form these storms take, as the residents of El Reno, Oklahoma, found out on 31 May, 2013.

At around 6pm local time, the El Reno tornado formed at an intersection about 15 kilometres (nine miles) southwest of the city. It soon began moving towards the town and rapidly increased in speed and size. Within 30 minutes it was moving at 80 kilometres per hour (50 miles per hour) and had ballooned into a massive maelstrom of thunder and wind 4.2 kilometres (2.6 miles) across. Luckily, it largely missed the city as it tore across 16 kilometres (ten miles) of farmland, ripping up crops and flattening farm buildings before dissipating at about 6:45pm. Sadly, three American storm chasers were among eight people killed by winds that reached speeds of up to 340 kilometres per hour (211 miles per hour).

Inside a mega twister

Get a closer look at how the El Reno tornado formed



Birth of a storm

Warm air near the ground surface rises, causing some of the rotating air to shift towards an upright orientation.

Wind shear

A cold front from the north confronts a warm front from the south, creating a horizontal tube of rotating air.

Did you know?

Relative to land area, the UK has more tornadoes than any other country, averaging 34 each year.

In a spin

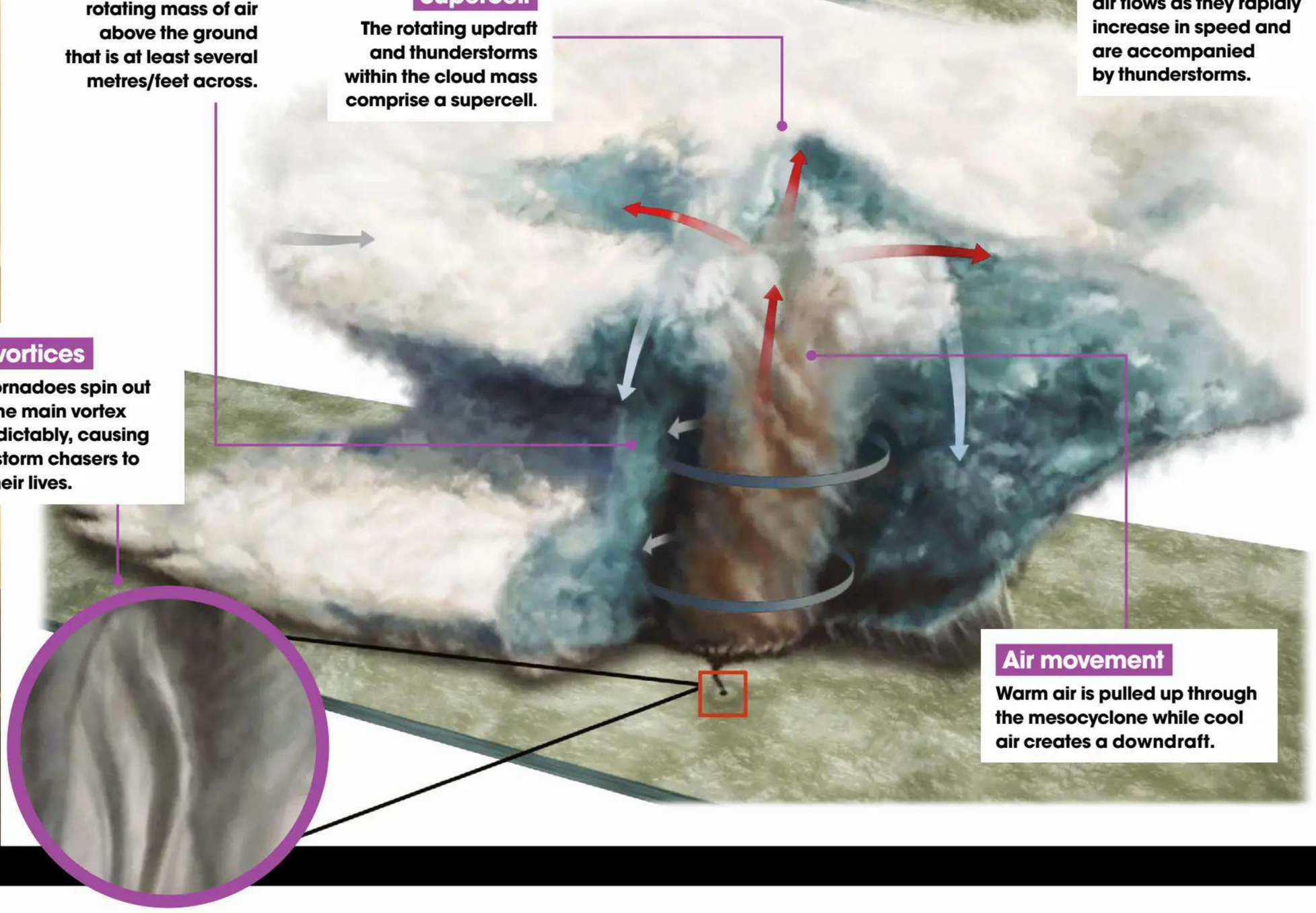
A vortex develops from the upended revolving air flows as they rapidly increase in speed and are accompanied by thunderstorms.

Mesocyclone

The vortex forms a mesocyclone: a rotating mass of air above the ground that is at least several metres/feet across.

Supercell

The rotating updraft and thunderstorms within the cloud mass comprise a supercell.



Subvortices

Mini tornadoes spin out from the main vortex unpredictably, causing three storm chasers to lose their lives.

Air movement

Warm air is pulled up through the mesocyclone while cool air creates a downdraft.

The El Reno tornado produced a massive funnel cloud and several subvortices

© Alamy; Illustration by Nicholas Forder

Most rainfall

Imagine having to mop up after getting almost two metres (6.6 feet) of rain in one day. That's what the citizens of the Cilaos, Reunion, had to do on 16 March, 1952 after an astonishing 1,870 millimetres (74 inches) of rain was believed to have fallen on the Indian Ocean island in just 24 hours. Yet that was just a shower compared with the 9,300 millimetres (366 inches) dumped on the residents of Cherrapunji, Mghalaya, India, throughout July 1861. Moreover, that came at the end of a 12-month period in which 26,461 millimetres (1,042 inches) poured on the town. Rain storms of this magnitude can occur in areas of mountainous terrain when moisture-laden air moves from a zone of high pressure over the ocean to a region of low pressure over land.

Largest raindrops
8.6mm (0.3in)
September 1995, Brazil & July 1999, Marshall Islands.

Snowy conditions at Paradise, Mount Rainier, are the result of airflows from the Pacific Ocean

-89.2°C (128.56°F)
Coldest directly recorded temperature: Vostok, Antarctica, 21 July, 1983.

Heaviest snowfall

Snow can be fun in moderate quantities, but more than enough fell on Mt Shasta Ski Bowl, California, in early 1959 to build an entire army of snowmen. Between 13 and 19 February, 4.8 metres (15.7 feet) settled on the resort, a record amount for a single snowstorm in Northern America.

However, the title of 'snowiest place on Earth' is claimed by Paradise in Mount Rainier National Park, Washington. On average, over 16.3 metres (53.5 feet) of snow blanketed the park every year between 1920 and 2011, with over 31 metres (102 feet) settling from February 1971 to February 1972.

Snow falls when moisture in the air precipitates under sub-zero temperatures, forming tiny snow flakes that clump together and fall as snow. The heaviest snowfalls occur when air has passed over large bodies of water and an unstable atmosphere forces it to rise more quickly than usual.

The mining town of Marble Bar guarantees a warm welcome but bring plenty of water

Hottest recorded temperature
Death Valley, US
10 July, 1913.

Longest heatwave

Meteorologists define heatwaves as periods when the temperature is above average for several consecutive days and nights. Such conditions are usually associated with high atmospheric pressure that compresses air near the surface, stifling circulation and preventing the formation of clouds that would otherwise help block out some sunlight. Unsurprisingly, record-setting heatwaves tend to occur in desert regions. The hottest air temperature ever measured on Earth is 56.7 degrees Celsius (134.06 degrees Fahrenheit), recorded at Greenland Ranch, Death Valley, California, on 10 July, 1913. Luckily for the wildlife, that heatwave lasted less than a week. At around 37 degrees Celsius (98.6 degrees Fahrenheit), the temperature in the world's longest ever heatwave was balmy by comparison. Yet, that was small consolation to the residents of Marble Bar in central Australia who got no relief for 160 consecutive days from October 1923 to April 1924.

On 22 January, 1943, Spearfish, South Dakota, went from -20 to +7°C (-4 to -44.6°F) in two minutes

Most dramatic temperature change

We say that people "change like the weather" if they display sudden mood swings and it's apt because the weather can be capricious.

The biggest temperature drop recorded in one day happened between 23 and 24 January, 1916 in Browning, Montana, when an influx of cold air sent temperatures plunging from +7 to -49 degrees Celsius (+44.6 to -56.2 degrees Fahrenheit). The biggest swing recorded over a 24-hour period, was in Loma, Montana, between 14 and 15 January, 1972. The first morning was a frigid -48 degrees Celsius (-54.5 degrees Fahrenheit), but the next was a comparatively more pleasant +9 degrees Celsius (48.2 degrees Fahrenheit).

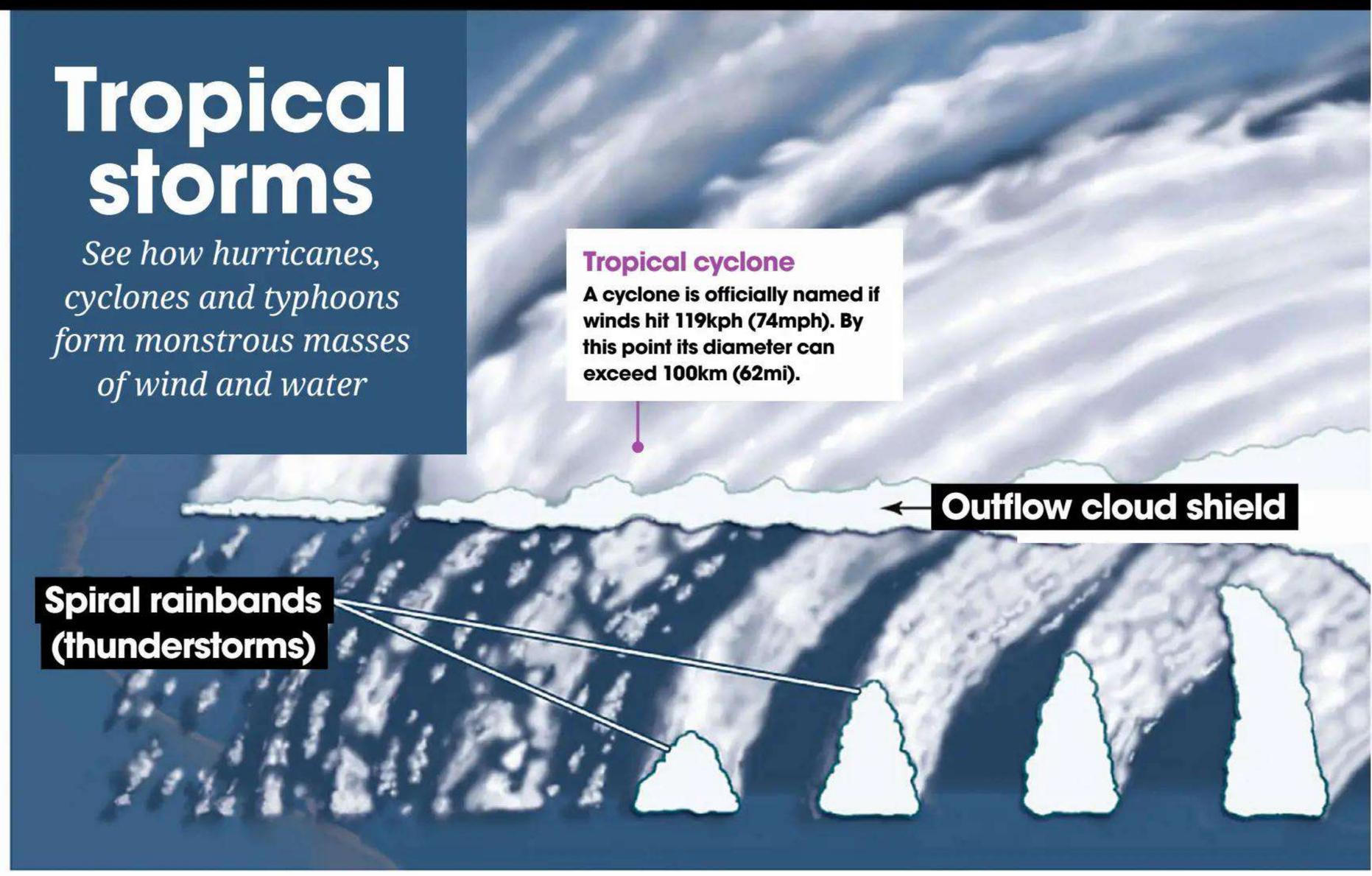
Native Americans call the winds that can create these conditions 'chinook' or 'snow eater'. Coming inland from the ocean and flowing over the side of a mountain range, these winds replace cold Arctic air with warm, dry air.

"Temperatures plummeted from +7 to -49°C (-4 to -44.6°F)"

© Alamy; Thinkstock; Wiki

Tropical storms

See how hurricanes, cyclones and typhoons form monstrous masses of wind and water



Top tempests

The super storms that left behind a trail of destruction

Biggest ever typhoon

Super Typhoon Tip developed out of a tropical storm over the western Pacific Ocean in early October 1979. Over the next three weeks it whipped up the sea and land between Micronesia and Japan with wind speeds that reached 306kph (190mph) over a diameter that stretched to 2,220km (1,379mi).

Strongest cyclone

Typhoon Tip is the most intense tropical cyclone on record. It holds the record for the lowest central pressure at just 870 millibars at sea level, as well as the highest sustained winds (10-minute average winds of 306kph/190mph).

Longest-lasting tropical storm

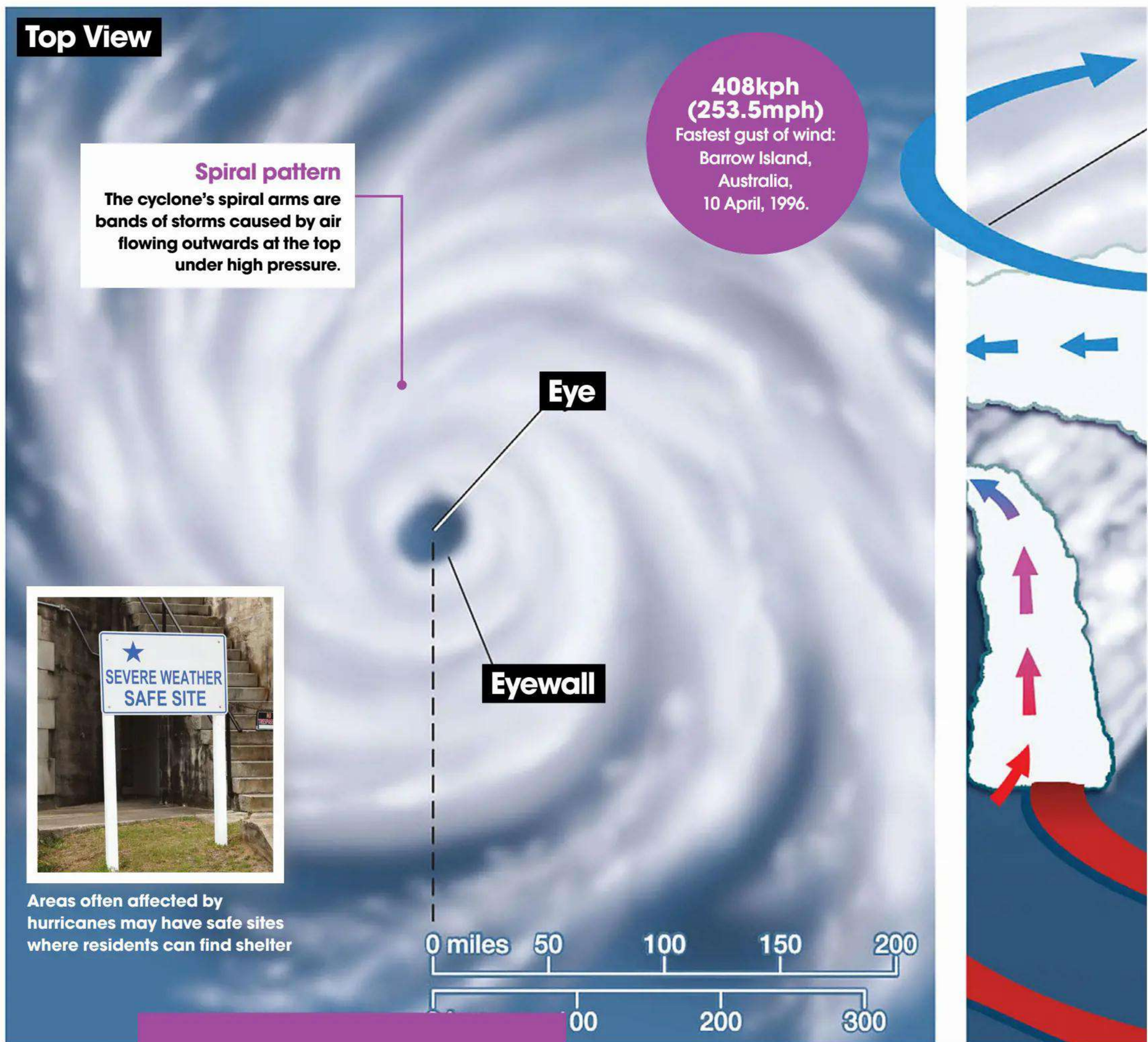
In 2024, Cyclone Freddy gained the world record for the longest-lasting tropical cyclone. It formed in February 2023 and travelled for more than five weeks (36 days) from northwest Australia across the Indian Ocean basin, with wind speeds of 260kph (160mph) at its strongest.

Most tornadoes spawned by a hurricane

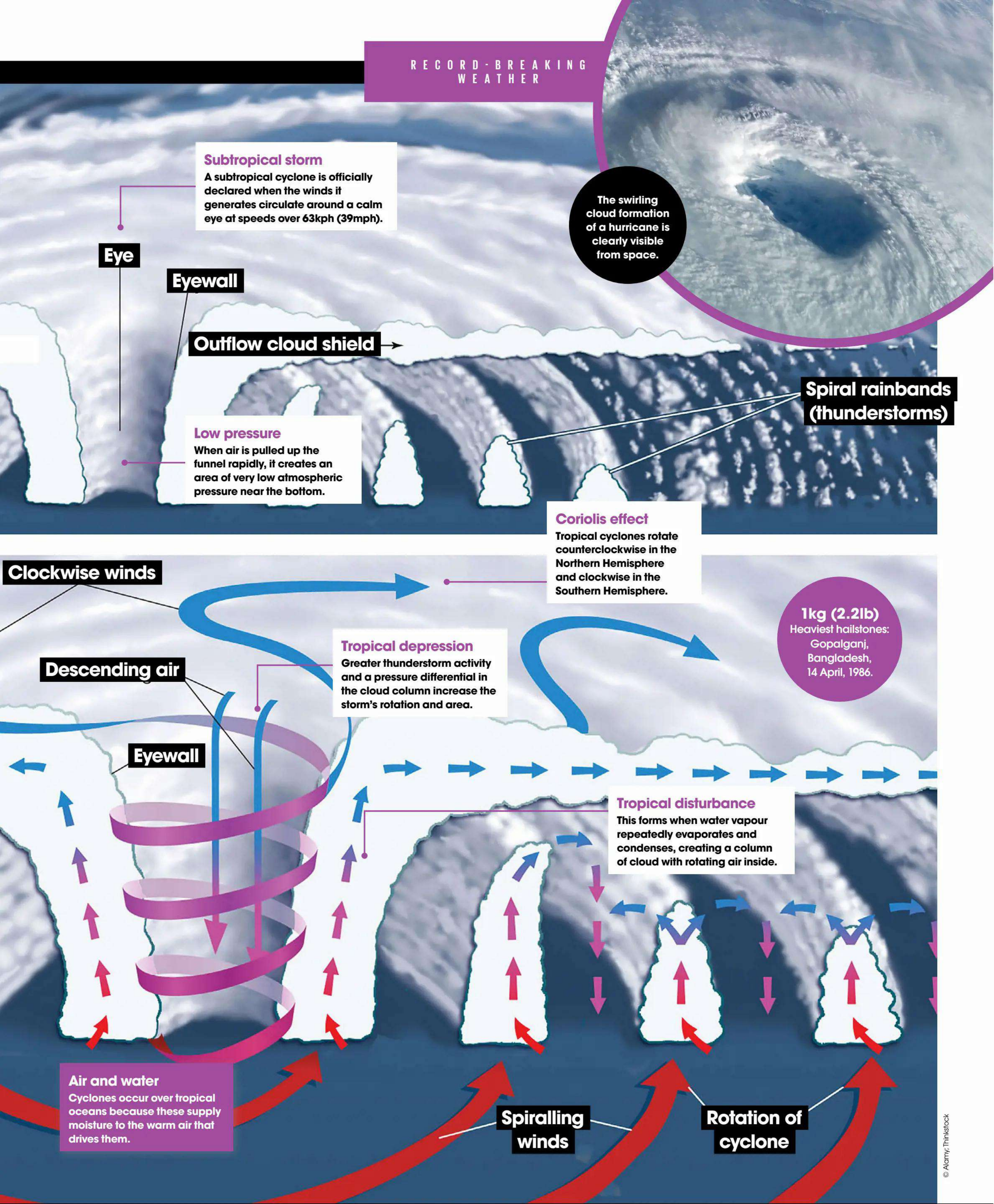
Hurricane Ivan developed into a Category 5 storm over the Caribbean Sea in September 2004. As it travelled across the southern US it spawned 119 tornadoes in just three days.

Deadliest cyclone

While its top wind speeds were well below those of the most powerful tornadoes, the Bhola Cyclone of November 1970 caused far more fatalities than any temperate zone twister. As it passed over parts of India and east Pakistan (now Bangladesh) it may have killed as many as 500,000 people.



Areas often affected by hurricanes may have safe sites where residents can find shelter



Subtropical storm
A subtropical cyclone is officially declared when the winds it generates circulate around a calm eye at speeds over 63kph (39mph).

Low pressure
When air is pulled up the funnel rapidly, it creates an area of very low atmospheric pressure near the bottom.

Coriolis effect
Tropical cyclones rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

Tropical depression
Greater thunderstorm activity and a pressure differential in the cloud column increase the storm's rotation and area.

Tropical disturbance
This forms when water vapour repeatedly evaporates and condenses, creating a column of cloud with rotating air inside.

Air and water
Cyclones occur over tropical oceans because these supply moisture to the warm air that drives them.

The swirling cloud formation of a hurricane is clearly visible from space.

1kg (2.2lb)
Heaviest hailstones: Gopalganj, Bangladesh, 14 April, 1986.

© Alamy; Thinkstock

What causes drought?

How a slight shift in wind patterns can have terrible consequences

Drought occurs when an extended period of high pressure brings very little rain

For areas that rely on regular rainfall to nourish vegetation, animals and a large human population, drought can be devastating, but in other parts of the world, hot, dry weather is a normal everyday occurrence. These arid climate conditions are caused by circulatory patterns of air in the Earth's atmosphere, known as Hadley cells.

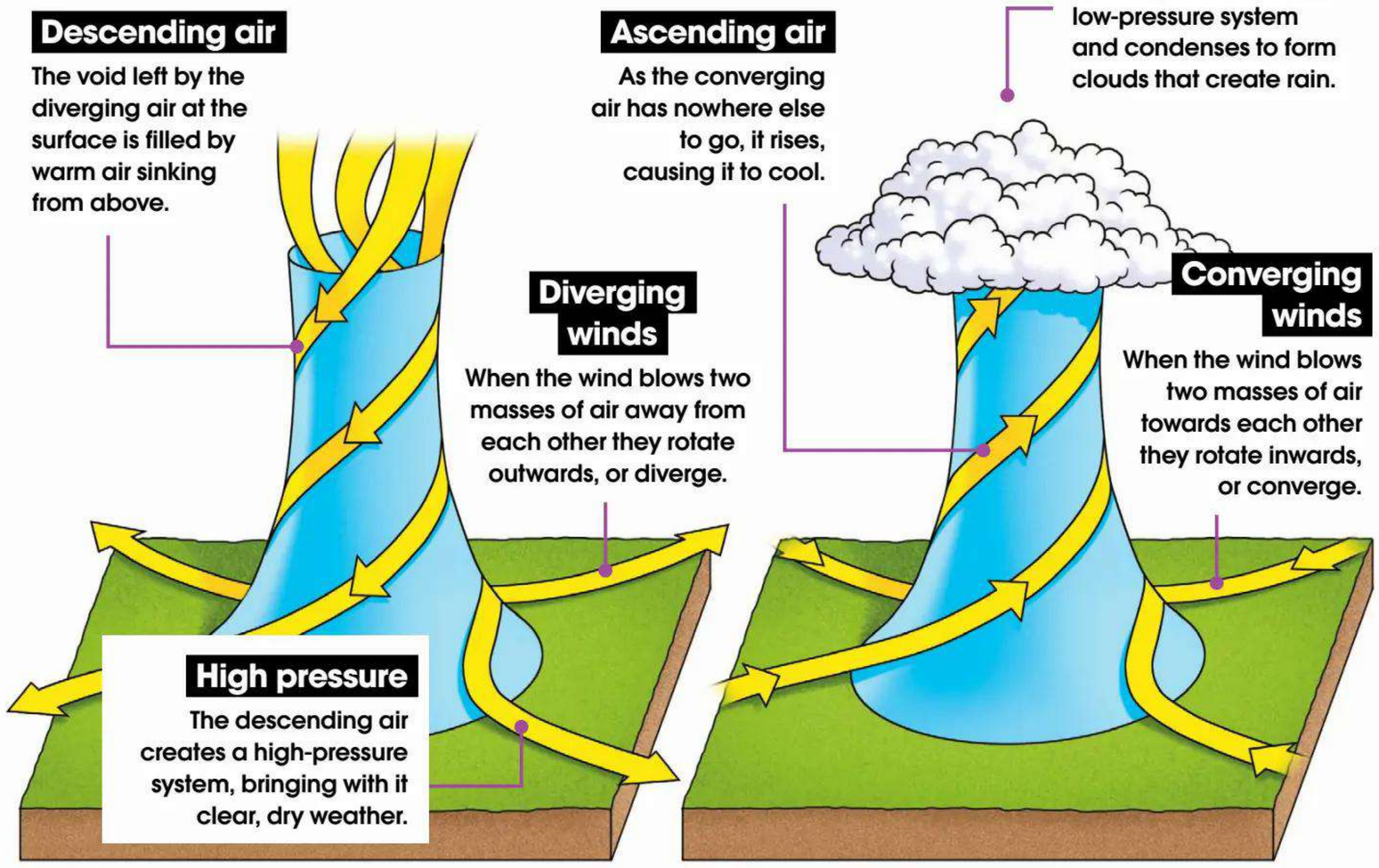
In this weather system, intense exposure to sunlight at the equator causes warm, moist air to rise. As the air rises, it cools again, forming a low-pressure system that results in regular thunderstorms across the region. Above these storms, the jet stream – a current that flows through Earth's upper atmosphere – carries the air towards higher latitudes until it eventually descends over the tropics north and south of the equator. As it falls, it creates a high-pressure system that is responsible for the arid conditions of the Sahara and other deserts that populate this region.

Slight changes in this movement of air can result in unusual – and sometimes catastrophic – weather activity, such as flooding and drought. For example, if the air that normally descends over the tropics in the Northern Hemisphere is carried further north by the jet stream, it can bring extended periods of high pressure to Europe. This can cause precipitation levels to fall below the expected average for the region, resulting in a period of non-seasonal drought.

Despite using advanced weather prediction models, experts are still only able to forecast drought when it is less than a month away, making it hard for countries to be prepared.

Convergence and divergence

How the movement of wind creates wet and dry weather



Killer heat waves and drought

A heat wave is a long period of hotter-than-usual weather – typically exceeding 5°C (9°F) above the average maximum temperature in the area. Prolonged exposure to high heat can cause hyperthermia, or heat stroke, when body temperature spirals out of control. It can be fatal without immediate medical attention. Higher-than-average air conditioning use can cause widespread power outages, making it difficult to keep cool in record temperatures.

Heat waves can also be accompanied by drought, spans of lower-than-average precipitation. Crop failure and wildfires can also contribute to deaths with prolonged periods of heat and drought. Some areas of the world, such as the Horn of Africa, commonly experience both heat waves and droughts. Heat waves are more common in semi-desert and inland desert areas, but they occur throughout the world. Hot air masses formed by systems of high pressure become stationary over an area and, in the absence of clouds, the ground and air both become excessively hot.

© Getty

India experiences the most dramatic monsoons in the world – many farmers there rely on the rains to sustain their agriculture

When you think of a monsoon, you probably think of torrential rains causing flooding, but there is more to these downpours than a single storm. A monsoon is actually a reversal of wind direction. These weather events cause heavy rain in summer and dry spells in winter as the prevailing winds shift as land heats and cools.

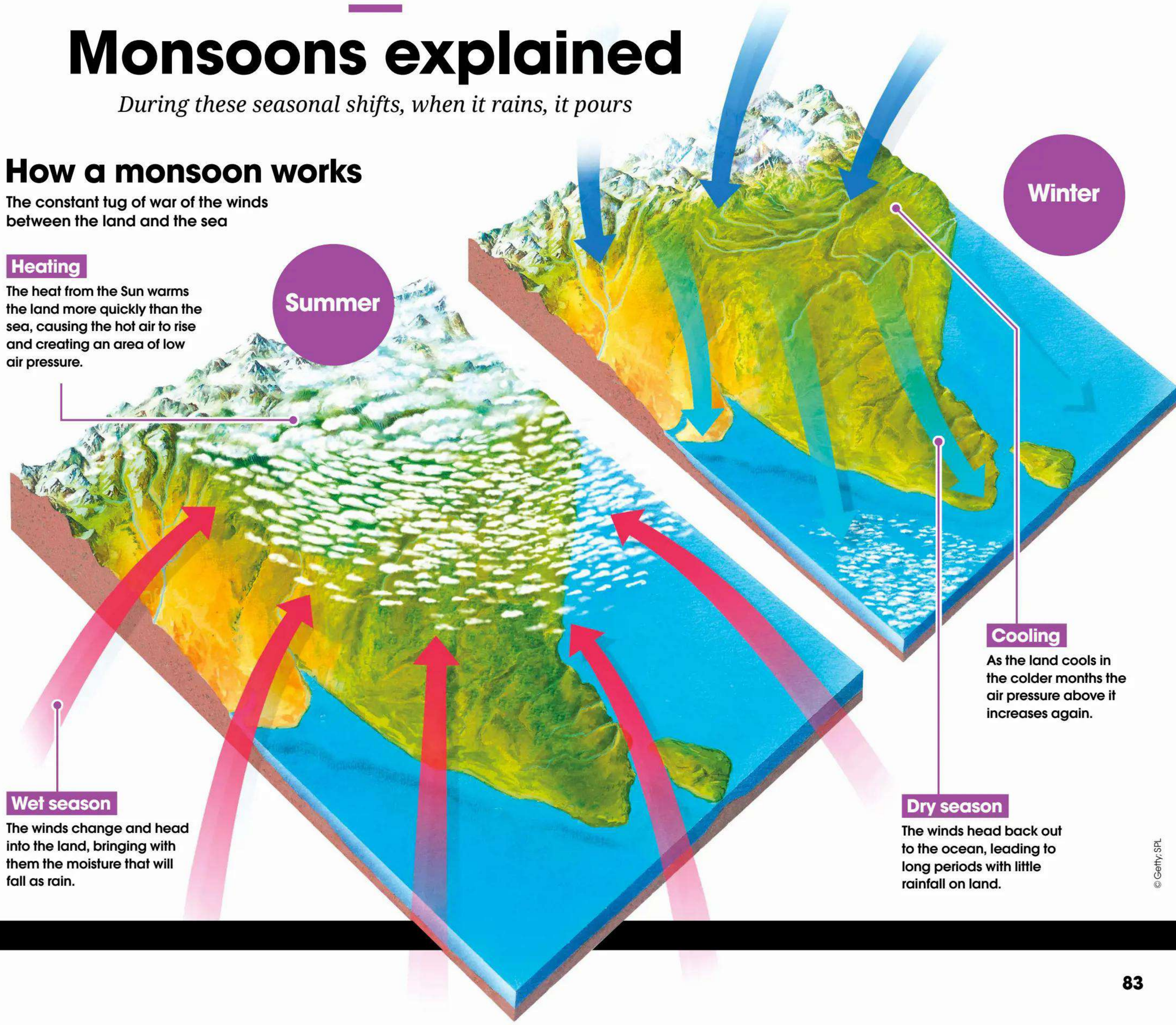
There are only specific areas of the world that are susceptible to this extreme weather, known as monsoon zones, and these are typically found in subtropical regions. Countries that suffer from regular monsoons include Bangladesh, India, Thailand and Sri Lanka, and they can experience anything from violent thunder and lightning to harsh dust storms.

Monsoons explained

During these seasonal shifts, when it rains, it pours

How a monsoon works

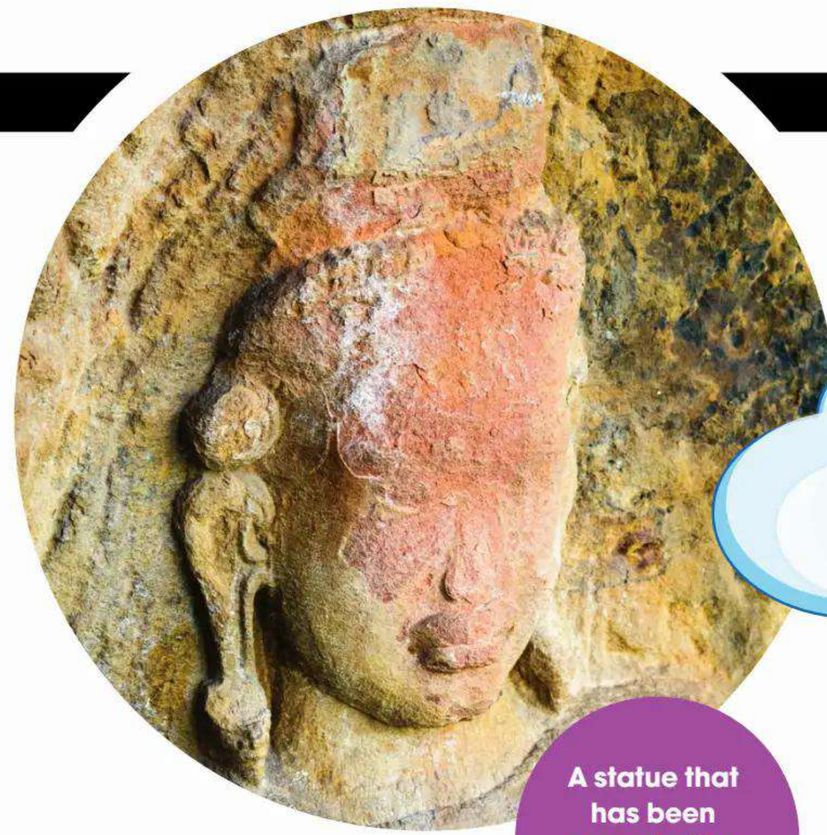
The constant tug of war of the winds between the land and the sea



© Getty; SPL

What is acid rain?

Some clouds can harbour water that kills trees and melts statues



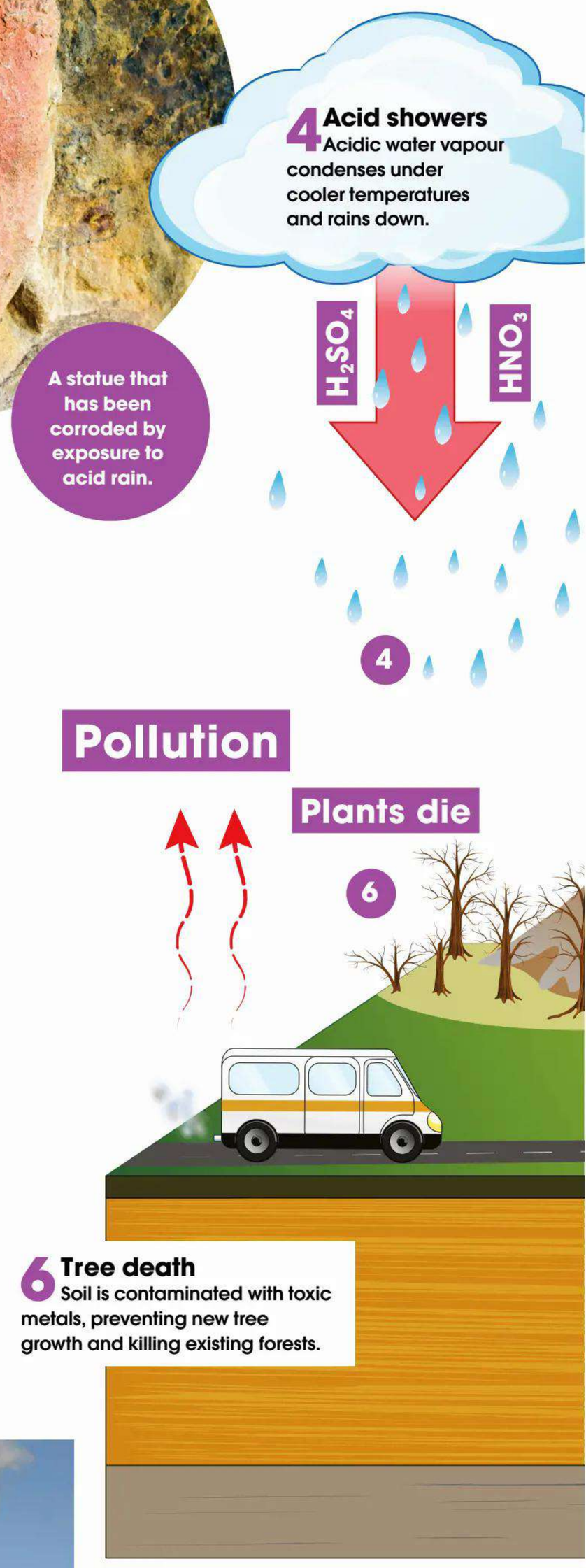
A statue that has been corroded by exposure to acid rain.

Acid rain is the broad term used to describe precipitation that is more acidic than normal. Typically, rainfall has a pH of 5.6 – anything below that level is considered acid rain. Of course, clouds aren't in control of the pH of their precipitation – just like the rest of the natural world, it's impacted by pollution emitted by cars and industry. The two main gas pollutants responsible for acid rain are sulphur dioxide (SO2), released as a byproduct of the fossil fuel industry, and nitrogen oxides (NOX) from vehicle exhausts. When these gases drift into the atmosphere, they interact with sunlight and water vapour to form sulphuric acid and nitric acid mists. Under warm temperatures, the clouds of acid mist remain as vapour. However, when temperatures cool, the vapour condenses and forms acidic droplets that fall to the ground as rain or snow. But industrial pollutants aren't the only way these gases enter the environment: natural sources also release SO2 and NOX into the atmosphere, such as volcanoes following a massive eruption.

Once in the environment, acid rain can wreak havoc on many ecosystems. For example, if you come across a forest of dying trees, there's a good chance that acid rain has played some part in their death. Acid rain can leach toxic metals from the soil, such as aluminium. Metals like aluminium prevent trees from taking up water and nutrients from the soil, ultimately starving them to death. At higher elevations, the acidic gases that don't make it into the clouds can also coat the surface of a tree's leaves, preventing them from being able to photosynthesise.

The direct effects of acid rain on human health, on the other hand, are few. However, in their gaseous states its ingredients can lead to many harmful respiratory issues, such as bronchitis and asthma attacks.

Alkaline lime being dumped into a lake in Sweden to reduce its acidic pH as a result of acid rain



Cleaning up the rain

It wasn't until 1963 that anyone knew what acid rain was. While studying the ecology of forests in New Hampshire, scientists discovered that rain samples were up to 100 times more acidic than they expected. At its peak, acid rain stripped forests and obliterated lakes across Europe, Canada and the US. In 1982, pH readings of 2.83 were recorded over the Great Lakes of the US and Canada. For comparison, lemon juice has a pH of between 2.0 and 3.0. During the 1990s, legislation around the world was introduced to curb the release of SO2. Between 1990 and 2017, the levels of SO2 emissions released in the US plummeted by 88 per cent, thanks to the Clean Air Act of 1990. To combat the release of SO2, many fossil fuel energy plants employ sophisticated air filters and 'scrubbers' to trap and store pollutants before they reach the atmosphere.

Did you know?
Most freshwater lakes have a pH of 6.5 to 8.5.

Industries with a greater risk of pollution, such as this cement factory, use sulphur dioxide scrubbers to minimise acid rain production

Cloud carriers

How pollutants move through the environment to destroy nature

Wind

2 On the move The world's wind currents move clouds across the continents.

5 Melting snow When acid snow melts, it can release large amounts of acid into the environment.

NOX

SO_2

3 Pollutants release Industrial SO2 and NOX are released into the atmosphere and are collected by clouds.

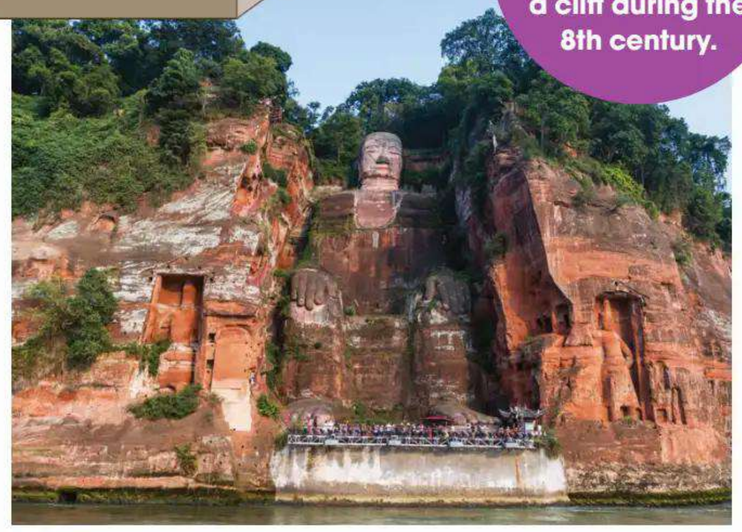
Evaporation

1 Evaporation Large-scale evaporation of lakes, seas and oceans creates water vapour-packed clouds.

7 Aquatic habitats Streams, lakes and marshes become acidic, reaching a pH level that's unsuitable for living creatures.

A monumental issue

One of the many consequences of acid rain is that it dissolves monuments and statues. When sulphuric acid and nitric acid come into contact with materials, such as marble and limestone, they can slowly dissolve a compound called calcite and erode the sculpture. The Leshan Giant Buddha in China is among the most afflicted by acid rain. As the world's largest stone Buddha, the statue was carved from a cliffside made of red sandstone around 1,200 years ago. A 71-metre-(233-feet-)high symbol of eternity and peace, the Leshan Buddha is an impressive feat of engineering. However, it's being dissolved by acid rain, leaving black and grey stains on its face and body. China is one of the world's largest fossil fuel users, which means that acid rain has already been a big environmental concern for the nation. But in 2023, 28.8 per cent of the monitored cities in China experienced acid rain, down from 44.4 per cent in 2013. Factories and power plants near the monument have been closed down to help prevent further damage.



The Leshan Giant Buddha, which was carved into a cliff during the 8th century.

© Shutterstock / Getty

Megafloods

Epic floods shaped our world but could they happen again today?

Northwest America hosts some of the strangest and most spectacular landforms on our planet. Scarred into the black rock are giant channels carved out by water – the largest is the Grand Coulee in Washington at 97 kilometres (60 miles) long.

In 1922, geologist J Harlen Bretz began investigating how these channels formed. He initially attributed them to the slow action of rivers, but the more he looked into it, the more unusual landforms he discovered. Among them were piles of gravel some ten storeys high and hills shaped like boat prows.

These gargantuan features were best explained by water tearing through the landscape – an unimaginably massive megaflood. The prow-shaped hills pointed in the direction of flow, while the gravel was dropped when the floodwaters receded.

Bretz tracked the source of this colossal torrent – possibly the largest flood in history – to the glacial Lake Missoula. During the last ice age, this lake formed behind a 610-metre (2,000-foot)-tall wall of ice. When this dam failed, around 15,000 years ago, the lake emptied in just 48 hours and the waters carved the Grand Coulee. They left ripples, like those on a streambed, but a monstrous nine metres (30 feet) high. The process would repeat itself over the next 2,000 years, carving out more colossal landmarks in North America.

Lake Missoula might be the biggest known megaflood, but it's by no means the only one. Indeed, during the last 1.8 million years, at least 27 gigantic freshwater floods have shaped our planet, carrying more than 100,000 cubic metres (3.5 million cubic feet) of water every second – equivalent to over 30 Niagara Falls!

We know less about giant floods from further back in Earth's history. "As you go back in time, you don't have the landforms preserved," says ice-age geologist Professor Philip Gibbard.

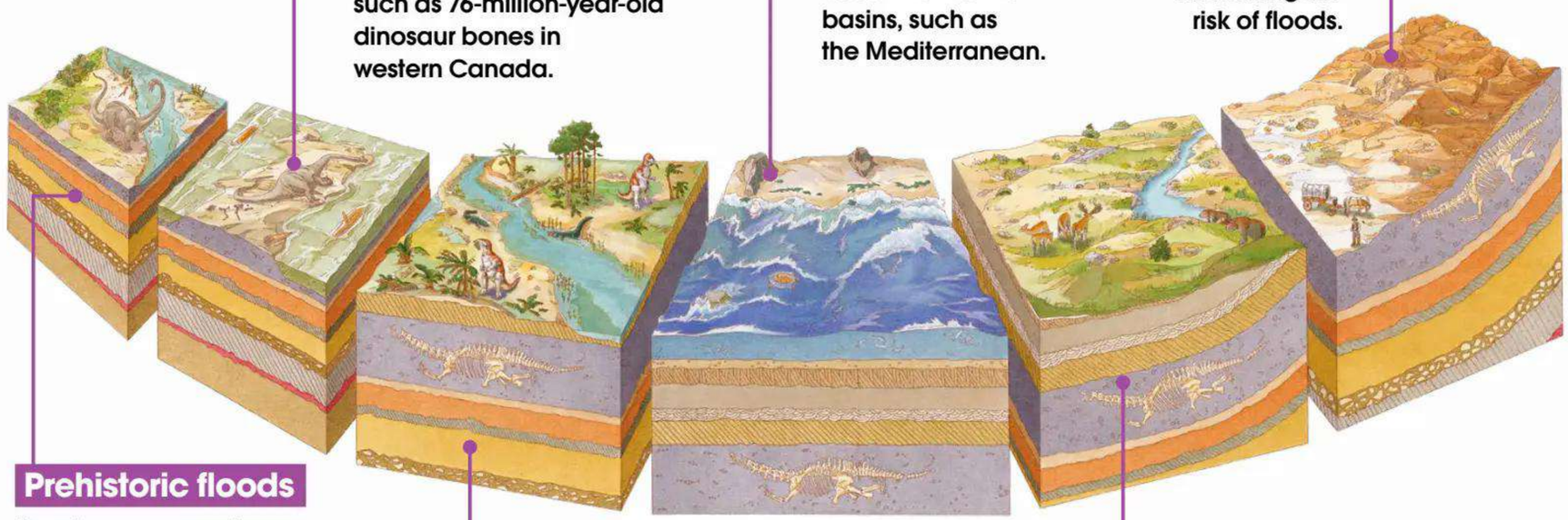
Water escaping from natural dams or glaciers is responsible for many of the biggest floods, including Lake Missoula. Gibbard continues: "You get substantial flooding if a major dam floods."

Among them is the megaflood that turned Britain into an island around 450,000 to 200,000 years ago, when sea levels were lower than today. A gigantic lake formed in what is today's North Sea behind a chalk ridge that once connected Britain to France by land. When the lake punched through the natural dam, floodwaters gouged a huge valley into the English Channel seabed (see the thermal imagery on the opposite page).

Other massive floods occurred when sea levels rose after an arid spell. For instance, around 5.3 million years ago, Atlantic waters spilled into the dried-up Mediterranean; the ocean eroded a channel through the Strait of Gibraltar, filling the sea in as little as two years.

Water world

What role have ancient floods played in forming the planet we know today?



Dinosaur graveyard

Ancient floods drowned prehistoric species, creating fossil sources, such as 76-million-year-old dinosaur bones in western Canada.

Sea level rise

Rising sea levels caused saltwater to flood into marine basins, such as the Mediterranean.

Present day

Humans build on flood plains, dam rivers and chop down trees – increasing the risk of floods.

Prehistoric floods

Floods occur anywhere there is water. When floodwaters retreat, nutrient-rich sediments are often left behind.

Ancient sediments

Evidence of prehistoric megafloods includes mineral deposits – such as microscopic zircon grains – dropped far downstream from their source.

Ice ages

Sea levels fell during ice ages. The ice formed natural dams across rivers, which collapsed to cause megafloods.

Did you know?

Nearly half of flash-flood deaths occur in vehicles. Just 0.6m (2ft) of water can set a car afloat.

Biggest floods in history

1 Altai Mountains, Asia

What may possibly be the biggest flood of all time occurred around 12,000 years ago. Ice dams collapsed on two interconnected lakes, emptying them into the Mediterranean Sea in an estimated five hours.

2 Wasilla, Alaska

When the glacial Lake Atna in Alaska breached a natural ice dam around 17,000 years ago, the megaflood released as much as 1,400km³ (336mi³) of water – that's enough to cover the area of Washington DC in water 8km (5mi) deep!

3 Bonneville flood, North America

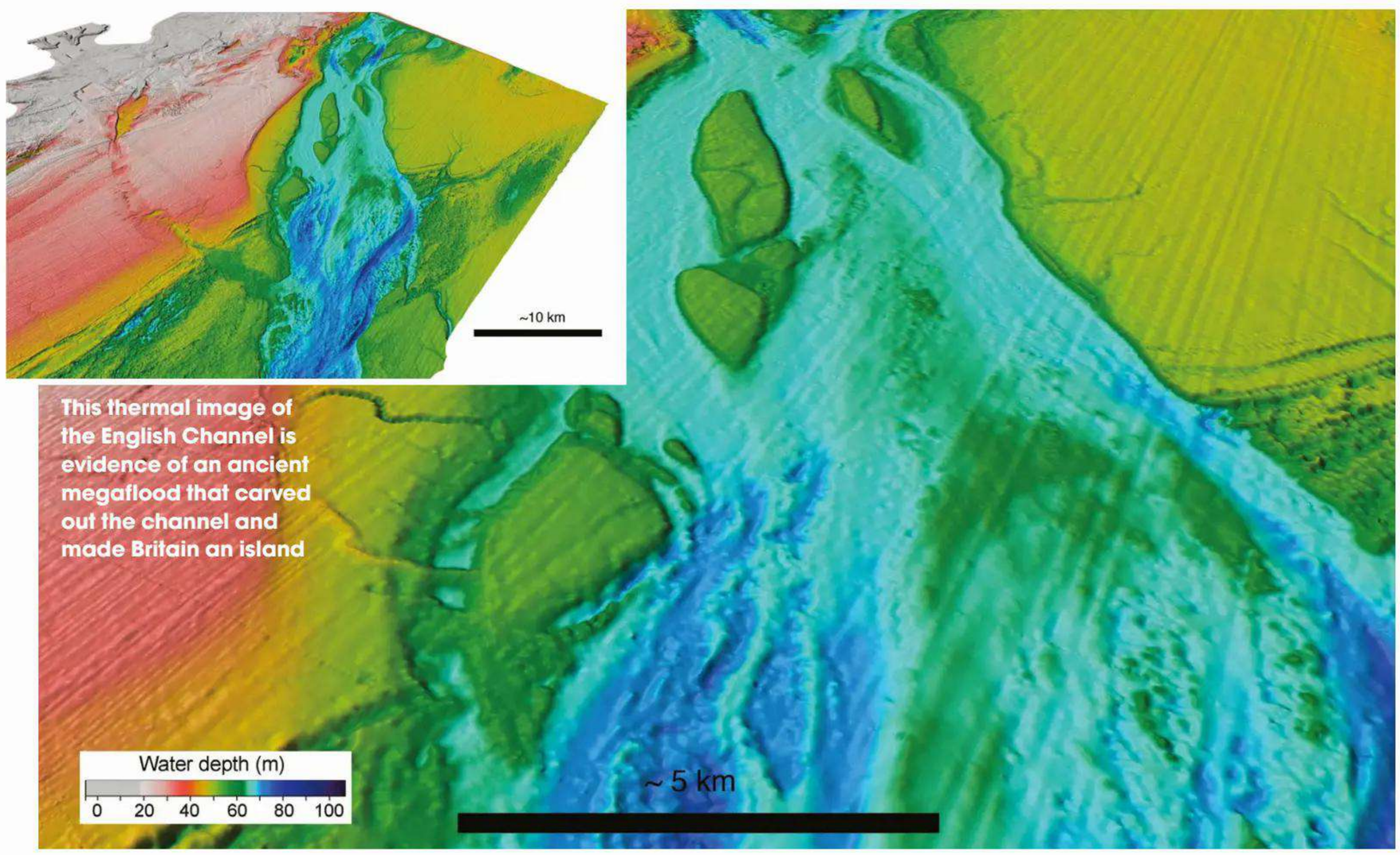
During a wet period 14,500 years ago, Lake Bonneville overflowed its basin. The floodwaters stripped soil, filled a 100m (330ft)-deep canyon to the brim and created immense and powerful waterfalls.

4 Yarlung-Tsangpo Gorge, Tibet

Gigantic lakes trapped in the Himalayas by ice dams helped erode this majestic gorge – which is possibly Earth's deepest. Evidence exists of several megafloods in the gorge during the last 2.5 million years.

5 Black Sea deluge

The biblical story of Noah and the great flood might well be based on a real historical event. Rising sea levels around 7,500 years ago may have flooded the Black Sea, destroying human settlements in the process.



This thermal image of the English Channel is evidence of an ancient megaflood that carved out the channel and made Britain an island

5 Facts Flood defences

1 Maeslant Barrier

Earth's largest movable storm surge barrier defends Netherlands' Rotterdam from floods. It spans a waterway 360m (1,181ft) across – as wide as the Eiffel Tower is tall.

2 Thames Barrier

This movable flood barrier is one of Earth's biggest and protects London against the North Sea. When raised, each of its ten steel gates is the height of a five-storey building.

3 St Petersburg Dam

The gigantic barrier includes 11 dams and is topped by a six-lane motorway. It was completed in 2011 after 300 years of almost yearly floods in the city.

4 West Closure Complex

The world's biggest pump station – designed to blast floodwaters back out to sea – is among £8.5bn ($14bn) of works to protect New Orleans from future hurricanes.

5 Delta Works

Described by some as a 'wonder of the world', this huge series of 300 dams, sluices and storm surge barriers protects the low-lying Netherlands from the sea.

Megafloods can also have a massive impact on the climate. The Lake Agassiz flood, for example, is blamed for a cold spell 12,900 years ago that sent North America's large mammals, like the woolly mammoth, extinct. Floodwaters poured into the North Atlantic, interfering with the ocean circulation that brings warm water to the poles, known as the Gulf Stream.

Fortunately floods as large as Lake Agassiz or Missoula are unlikely to happen today. The biggest deluges were associated with giant ice sheets that swathed the northern hemisphere during the last ice ages. The ice released torrents of meltwater and trapped huge lakes behind ice dams, which gradually succumbed to global warming. Only the Greenland and Antarctic ice sheets, and a few other ice caps, remain.

"Jökulhlaup, or glacier bursts, occur when a volcano erupts under an ice cap, eg the 1996 Vatnajökull eruption"

But that doesn't count megafloods out altogether. Among the 27 known big freshwater floods in the last 1.8 million years, eight occurred after 1900. According to Gibbard: "We could experience a megaflood today. Look no further than Iceland where we see jökulhlaup."

Jökulhlaup, or glacier bursts, occur when a volcano erupts under an ice cap, such as the 1996 Vatnajökull eruption in south-east Iceland. A torrent of meltwater flooded from beneath the ice, wiping out anything that stood in its way, including bridges, roads and power lines. It's estimated that peak flows reached 50,000 cubic metres (1.8 million cubic feet) of water per second in this massive jökulhlaup.

Another cause of giant floods, says Gibbard, is where "you have a volcanic lake, and the volcano erupts and breaches the barrier holding the water in the crater. You can get a deadly mudflow, sweeping away everything in its path." An example is Lake Taupo, New Zealand's largest lake, which flooded during an eruption some 1,800 years ago.

Debris from volcanoes can also block rivers. An eruption in Mount St Helens about 2,500 years ago caused Spirit Lake to empty

Focus on flash floods

In August 1997, an Arizona desert canyon became a death trap for 11 hikers when they were caught out by a flash flood. A sudden thunderstorm quickly filled the narrow walls with tumbling water and they had nowhere to escape.

Flash floods occur within a few hours of violent rainfall. Although hard to believe, they are common in deserts, which lack the soil to soak up incoming rain. Water hurtles downhill over bare rock, rapidly turning creeks kilometres/miles from the storm into raging rivers.

Desert plants like blue palo verde depend on flash floods for survival; the fast-moving water disperses seeds downstream and abrades their hard coating, helping them to germinate.

The walls of Antelope Canyon, AZ, have been shaped by repeated flash floods

catastrophically. More than 260,000 cubic metres (9.2 million cubic feet) of water per second flooded downstream. This was like a bathtub overflowing by comparison to Lake Missoula, though, which emptied at an incomprehensible 17 million cubic metres (600 million cubic feet) per second. Similar floods would have been likely after the 1980 eruption of Mount St Helen's if mitigation measures weren't undertaken and the lake had not been drained via a pipeline.

So how do these megafloods compare to more common flooding events, like we've seen in recent months? "They're orders of magnitude greater," explains Gibbard: "We're talking stuff that's incredibly dramatic. Much larger scale than conventional flooding of rivers."

Rivers bursting their banks are the most common cause of flooding today. Excessive rain or rapid snowmelt can overfill a river channel, causing water to spill out over low-lying land. Waterlogged or parched soil can also cause water levels to rise rapidly. Even a little rainfall cannot be soaked up by the ground so rush straight into the river, causing a flood.

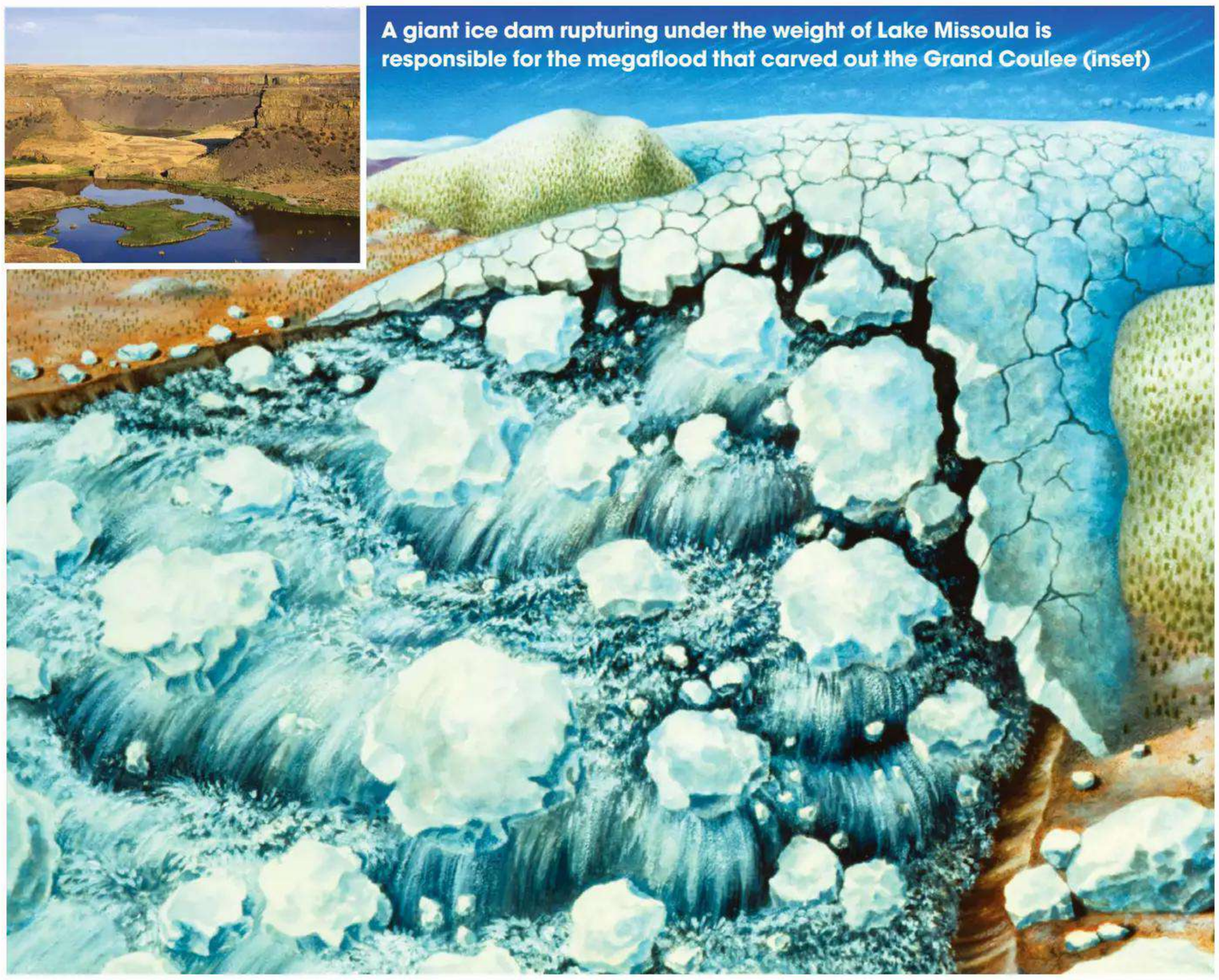
Human activity – such as building hard tarmac roads – is making river flooding even worse, warns Gibbard. "The inevitable consequence of covering the landscape with impermeable materials is like wrapping it in a polythene bag. [More and more] water runs straight into our rivers."

With sea levels predicted to rise dramatically this century – and climate change likely to boost storm power and frequency – the risk of coastal flooding is on the rise. Coastal flooding occurs when a storm blows seawater inland or when a tsunami – a giant wave usually generated by an oceanic earthquake – hits the shore.

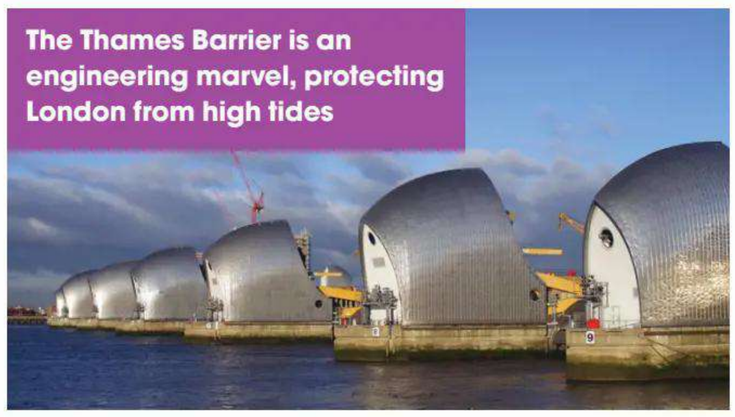
The big question is, can we predict future megafloods? "Not easily," says Gibbard. "We know volcanoes erupt under ice caps in Iceland. People are trying to predict volcanic activity, but we're not there yet."

The next 'megaflood' might come from a humanmade dam rupturing during an earthquake. Gibbard explains, "Anywhere where water is stored on less-than-firm ground might go. The sheer height of water behind those barrages must be enormous."

It's a real risk. Out of over 91,000 American dams, around 25,000 are considered hazardous. Among them is the Lake Isabella Dam in California. A strong earthquake could send around 700 million cubic metres (2.5 billion cubic feet) of water tumbling downriver. For now though the best we can do is never to underestimate the mighty power of water.



A giant ice dam rupturing under the weight of Lake Missoula is responsible for the megaflood that carved out the Grand Coulee (inset)



The Thames Barrier is an engineering marvel, protecting London from high tides

How we defend against floods

An estimated 37 per cent of the world's population live within 100 kilometres (62 miles) of the coast – many in major cities like London, New York and Tokyo. They are at risk of flooding from unusually high tides and storm surges.

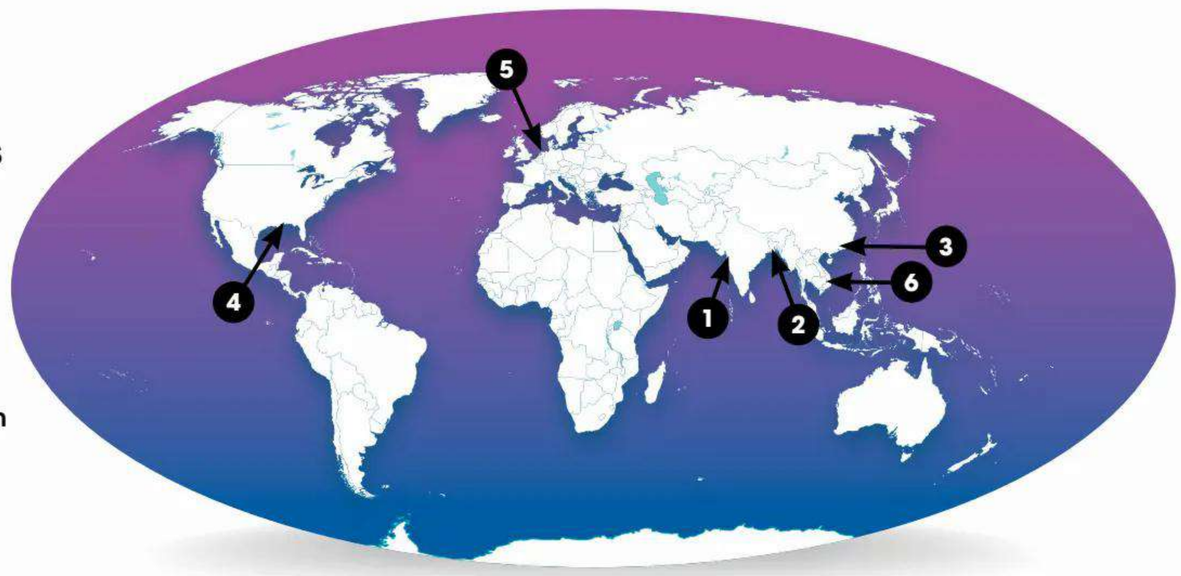
Many cities protect themselves from this threat with hi-tech barriers, dams or sluice gates. For example, the Thames Barrier downstream of London is a set of gates that lie flat on the riverbed when open. The gates rotate upright when a storm surge heads inland from the North Sea, or heavy rainfall raises the river level of the Thames enough that normal tides will cause flooding. Each gate can hold back 90,000 tons of water.

Other flood defence systems have permanent dams with sliding sluice gates to control water flow. The Oosterscheldedam in the Netherlands – the largest tidal barrier on Earth – is nine kilometres (5.6 miles) long and has 62 colossal gates; these raise to make the structure watertight.

New Orleans was flooded in Hurricane Katrina in 2005 – one of the deadliest storms in US history. Much of the city lies below sea level and depends on humanmade embankments to keep out water. During the hurricane, these levees broke. The US Army had to renovate the levees and build new defences, including a pumping station able to pump 540 cubic metres (19,000 cubic feet) of rainwater every second – enough to empty an Olympic-sized swimming pool in five seconds.

Flood-prone places around the globe

1 India
2 Bangladesh
3 Guangzhou, China
4 New Orleans, USA
5 The Netherlands
6 Ho Chi Minh City, Vietnam



© Professor Sanjeev Gupta and Dr Jenny Collier, Department of Earth Science and Engineering, Imperial College London; SPL; Thinkstock; Corbis

Mega tsunami

Among the most epically destructive forces on Earth, tsunamis cause catastrophic levels of carnage, unearthing trees, levelling buildings and ending life

Tsunamis form through a complex, multi-stage process that emanates from the massive energy release of a submarine earthquake, underwater or coastal landslide, or volcanic eruption.

The first stage in this formation begins when the tectonic upthrust caused by the quake or impulse event causes massive amounts of ocean water to be displaced almost instantaneously. This action kick-starts a simple series of progressive and oscillatory waves that travel out from the event's epicentre in ever-widening circles throughout the deep ocean. Due to severe levels of energy propagated from the impulse, the waves build in speed very quickly, reaching up to an incredible 805 kilometres per hour (500 miles per hour). However, due to the depth of water, the speed of the waves is not visible as they expand to have incredibly long wavelengths that can stretch between 96.6 to 193 kilometres (60 to 120 miles). Because of this, the wave amplitudes (the wave height) are also very small as the wave is extremely spread out, only typically measuring 30 to 60 centimetres (12 to 24 inches). These long periods between wave crests – coupled with their very low amplitude – also mean that they are particularly difficult to detect when out at sea.

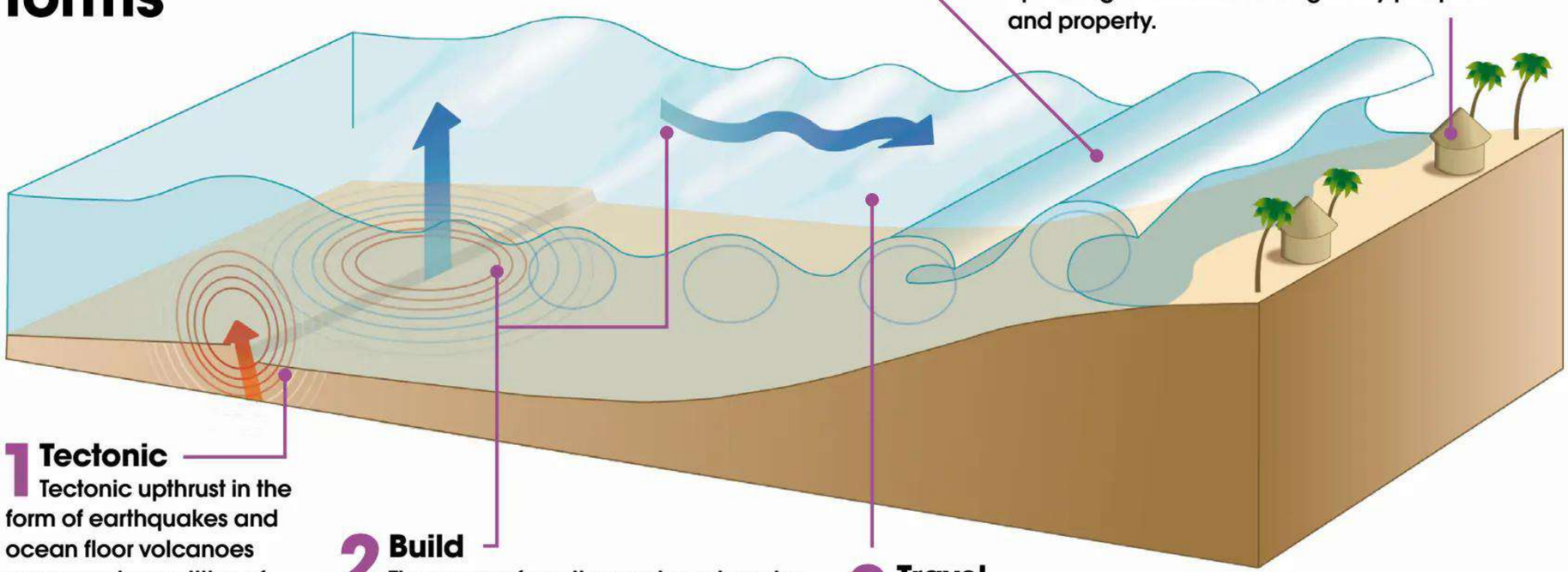
Once generated, the tsunami's waves then continue to build in speed and force before finally approaching a landmass. Here the depth of the ocean slowly begins to reduce as the land begins to slope up towards the coastline. This sloping of the seabed acts as a braking

© Evilarry

How a tsunami forms

4 Approach
As the tsunami waves approach the coastline of a landmass they are slowed dramatically by the friction of their collision with the rising seabed. As the velocity lessens, however, the wavelengths become shortened and amplitude increases.

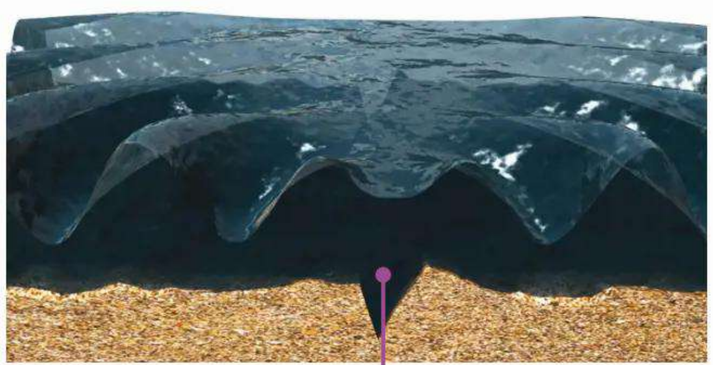
5 Impact
Finally, with the wavelength compressed and heightened to large levels (often between 5-10m/16.4-33ft), the giant waves collide with the shore causing massive damage. The succeeding outflow of water then continues the destruction, uprooting trees and washing away people and property.



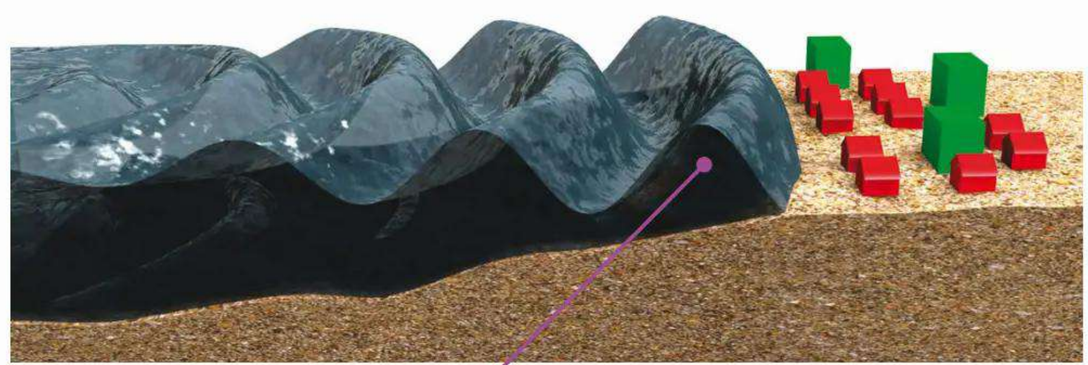
1 Tectonic
Tectonic upthrust in the form of earthquakes and ocean floor volcanoes cause vast quantities of water to be displaced in a very short space of time, generating a massive amount of energy.

2 Build
The energy from the quake or impulse causes a train of simple, progressive oscillatory waves to propagate over the ocean surface in ever-widening circles at speeds as fast as 805kph (500mph).

3 Travel
The wavelengths of the tsunami continue to grow, with the waves' periods (the lengths of time for successive crests or troughs to pass a single point) varying from five minutes to more than an hour.



Cause
Tsunamis initiate when an earthquake causes the seabed to rupture (bottom centre), which leads to a rapid decrease in sea surface height directly above it.



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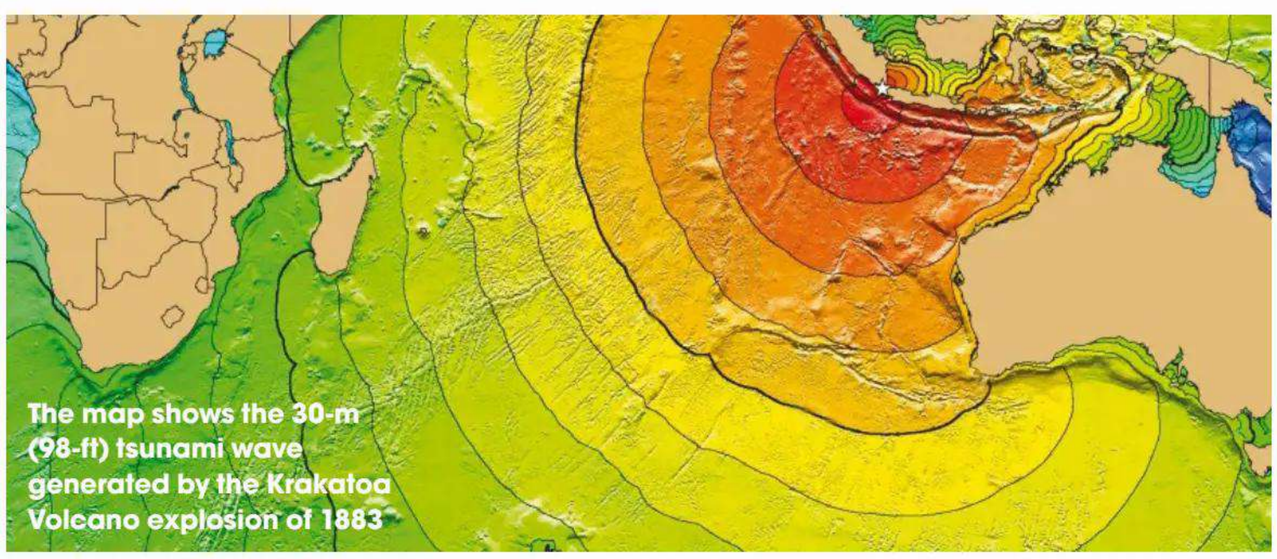
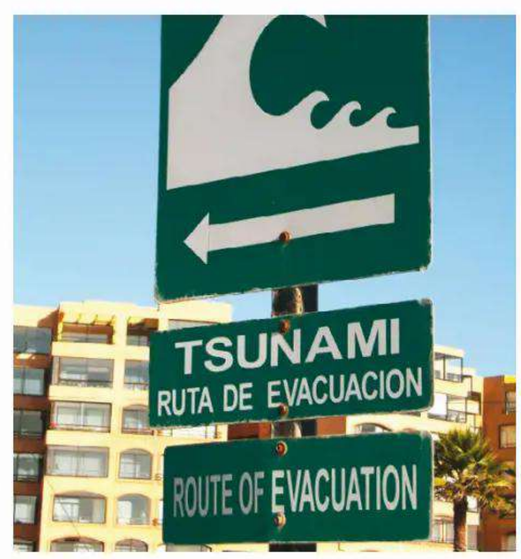
Effect
As the tsunami reaches the shore the shallow, long and exceedingly fast waves pile up, reducing the wavelength and increasing their height dramatically.



The map shows the 30-m (98-ft) tsunami wave generated by the Krakatoa Volcano explosion of 1883

© NOAA



No need to ask what this sign means

mechanism for the high-velocity tsunami waves, reducing their speed through colossal friction between the water and the rising earth. This dramatic reduction in speed – which typically takes the velocity of the tsunami to 1/10th of its original speed – also has the effect of reducing the length of its waves, bunching them up and increasing their amplitude significantly. Indeed, at this point coastal waters can be forced to raise as much as 30 metres (98.4 feet) above normal sea level in little over ten minutes.

Following this rise in sea level above the continental shelf (a shallow submarine terrace of continental crust that forms at the edge of a continental landmass) the oscillatory motions carried by the tsunami are transferred into its waters, being compressed in the process. These oscillations under the pressure of the

Historic tsunamis

Big

1 Messina
The Messina earthquake of 1908 triggered a large tsunami 12-m (39-ft) high that levelled entire buildings and killed more than 70,000 people in Sicily and southern Italy. The earthquake that generated it measured 7.5 on the Richter scale and caused the ground to shake for between 30 and 40 seconds.

Bigger

2 The Valdivia earthquake
The Valdivia earthquake of 1960 caused one of the most damaging tsunamis of the 20th century. Thousands of people were killed by it and it stretched as far as Hilo, Hawaii. Measuring 9.5 on the Richter scale, the earthquake caused waves up to 25m (82ft) to assault the Chilean coast. The earthquake also triggered landslides and volcanic eruptions.

Biggest

3 Lituya Bay
After an earthquake caused a landslide at the head of Lituya Bay, Alaska, in July 1958, a massive tsunami was generated measuring over 524m (1,719ft) in height, taller than the Empire State Building. Amazingly, despite the awesome height of the tsunami, only two fishermen operating in the bay were killed by it.

approaching water are then forced forwards towards the coast, causing a series of low level but incredibly fast run-ups of sea water, capable of propelling and dragging cars, trees, buildings and people over great distances. In fact, these run-ups are often responsible for a large proportion of the tsunami's damage, not the giant following waves. Regardless, however, following the run-ups the tsunami's high-amplitude waves continue to slow and bunch into fewer and fewer megawaves before breaking at heights between five and ten metres (16 and 33 feet) over the immediate coastline, causing great damage and finally releasing its stored energy.

Due to the severe hazards that tsunamis pose, research into their causes and tracking of their formation has increased through the 20th and 21st centuries. Currently, the world's oceans are monitored by various detection and prevention centres, such as the Pacific Tsunami Warning Center (PTWC) based in Honolulu, Hawaii.

"Due to severe levels of energy propagated from the impulse, the waves build in speed very quickly"

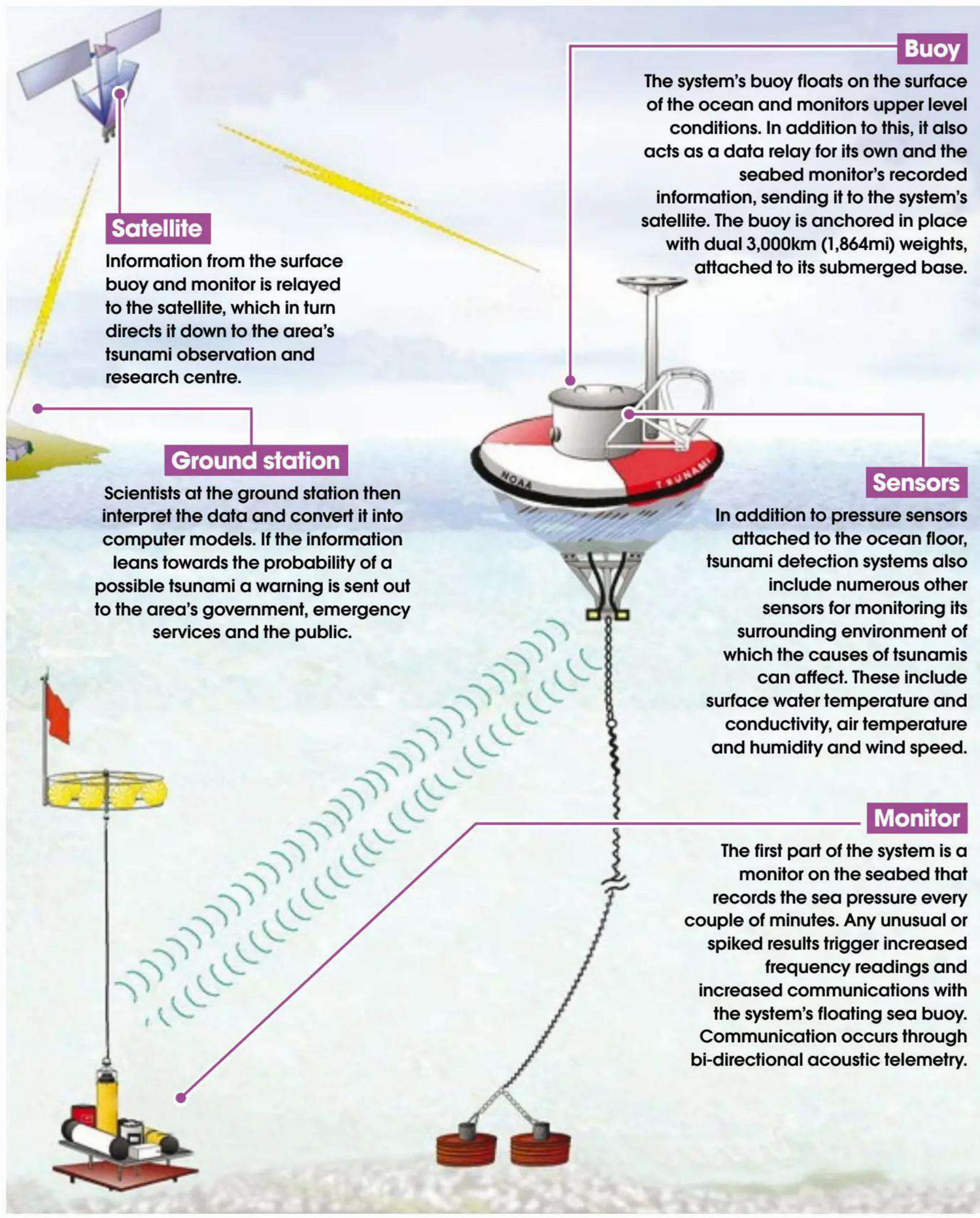
Set up back in 1949, the PTWC utilises a series of monitoring systems that deliver daily seismic and oceanographic data, with information transferred to it and other stations by satellite connection. This is one of two American-run centres that monitors the Pacific Ocean and it is responsible for detecting and predicting the size and target of approaching tsunamis.

Tsunami prevention has also seen advances as construction techniques and materials have developed over the past century. Now areas prone to tsunamis, such as Japan's west coast, are fitted with large-scale sea walls, artificial deep-sea barriers, emergency raised evacuation platforms and integrated electronic warning signs and klaxons in coastal resorts and ports.

Areas that have been affected by tsunamis are also fitted with physical warning signs and have evacuation routes that allow for large numbers of people to quickly move inland. However, despite many advances being made to ensure prone areas are protected, due to the transcontinental nature of tsunamis, remote or under-developed areas are still affected regularly, the consequences of which were shown in the disastrous 2004 tsunami in the Indian Ocean that claimed over 200,000 lives.

The DART II tsunami detection system

Introducing the system and technology that aids scientists in detecting upcoming tsunamis



The devastated Marina beach in Chennai after the Indian Ocean tsunami struck

© NOAA

A tsunami emergency evacuation platform in Japan

© Kotoviski

The 2004 tsunami striking the coast of Thailand

The 2004 Indian Ocean tsunami

Claiming the lives of over 200,000 people, the Indian Ocean tsunami of 2004 was literally off-the-scale in terms of both damage and destruction

The stats 2004 Indian Ocean tsunami

Height **30m (98ft)**

230,000 Deaths

Money raised **$7bn**

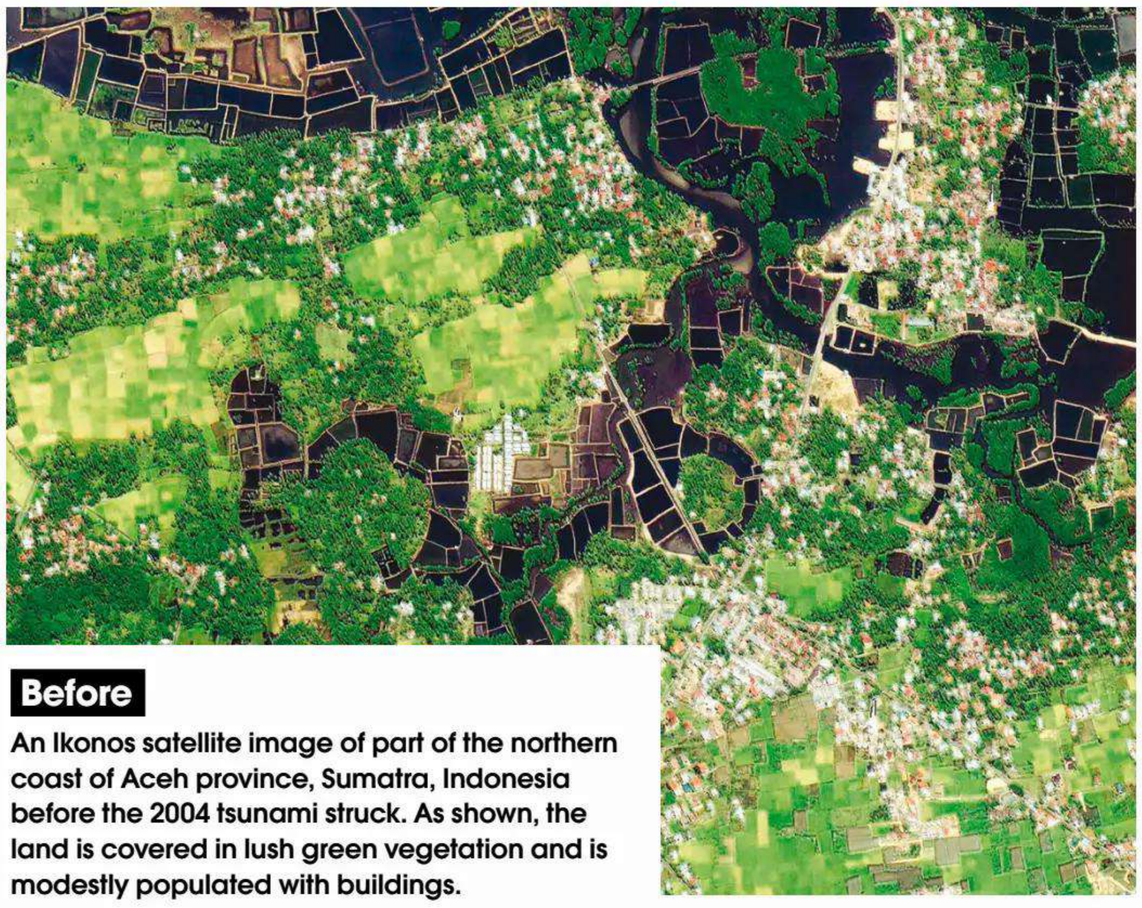
14 Countries affected

Earthquake magnitude **9.3**

On 26 December 2004, an undersea megathrust earthquake caused a huge earth subduction and triggered a series of devastating tsunamis that ravaged almost all landmasses bordering on the Indian Ocean, killing over 230,000 people in 14 different countries. The hypocentre of the main earthquake was approximately 161 kilometres (100 miles) off the western coast of northern Sumatra and emanated from the ocean floor 30.6 kilometres (19 miles) below the area's mean sea level. Here, a massive rupture in the ocean floor caused massive tectonic plate movement – an event felt as far away as Singapore – as well as the creation of numerous secondary faults that elevated the height and speed of generated waves to titanic levels.

The fallout from the earthquake and resulting tsunami was the worst for over 50 years, with the event releasing a total of 1.1x107 joules of energy (comparable to 26.3 megatons of TNT, and over 1,502 times the energy released by the Hiroshima atomic bomb). Indeed, the rupture was so severe it slightly altered the Earth's rotation, causing it to wobble on its axis by up to 2.5 centimetres (one inch).

Further, when the British Royal Navy vessel HMS Scott surveyed the seabed around the earthquake zone with a multi-beam sonar system, it revealed that it has drastically altered its topography. The event caused 1,500-metre (4,921-feet) ridges to collapse into massive landslides. The momentum of the water displaced by tectonic upshift had also dragged massive million-ton rocks over ten kilometres (6.2 miles) on the seabed and an entirely new oceanic trench had been exposed.



Before

An Ikonos satellite image of part of the northern coast of Aceh province, Sumatra, Indonesia before the 2004 tsunami struck. As shown, the land is covered in lush green vegetation and is modestly populated with buildings.

After

An Ikonos satellite taken on 29 December 2004, three days after the tsunami struck. As can be seen now, almost all of the immediate coastline has been completed submerged underwater and the huge, lush plains of vegetation have been severely encroached upon and washed away. Many buildings have also been submerged or destroyed.

2x © Science Photo Library

Super storms

They're wild and deadly disaster-movie stars – discover the secrets behind Earth's worst storms

Severe storms have caused some of the world's worst weather and inspired several highly implausible movies. Responsible for countless deaths and damage, super storms, scientists fear, could get stronger in the future due to climate change.

The giant hailstones, violent winds, pounding rain and huge tornadoes that make wild weather a disaster-movie staple are mainly associated with two weather systems – the supercell thunderstorm and hurricanes. Depending on location and strength, hurricanes are also called typhoons, severe tropical cyclones or severe cyclonic storms.

Hurricanes are around a hundred times bigger than supercell storms, but supercells pack vast energies into a thunderstorm less than nine kilometres (5.6 miles) across. Supercell storms can spawn violent tornadoes, which can reach wind speeds of up to 512 kilometres per hour (318 miles per hours), and generate giant hail. In 2010 a record-breaking 20-centimetre (eight-inch) diameter hailstone was found in South Dakota.

Although hurricane wind speeds are slower, hurricanes contain lots of energy and can cause severe damage over large areas. In 1992 Hurricane Andrew did an estimated £12-16 ($15-$30) billion of damage. Widespread torrential rain can cause flooding and storm surges often inundate coastal areas.

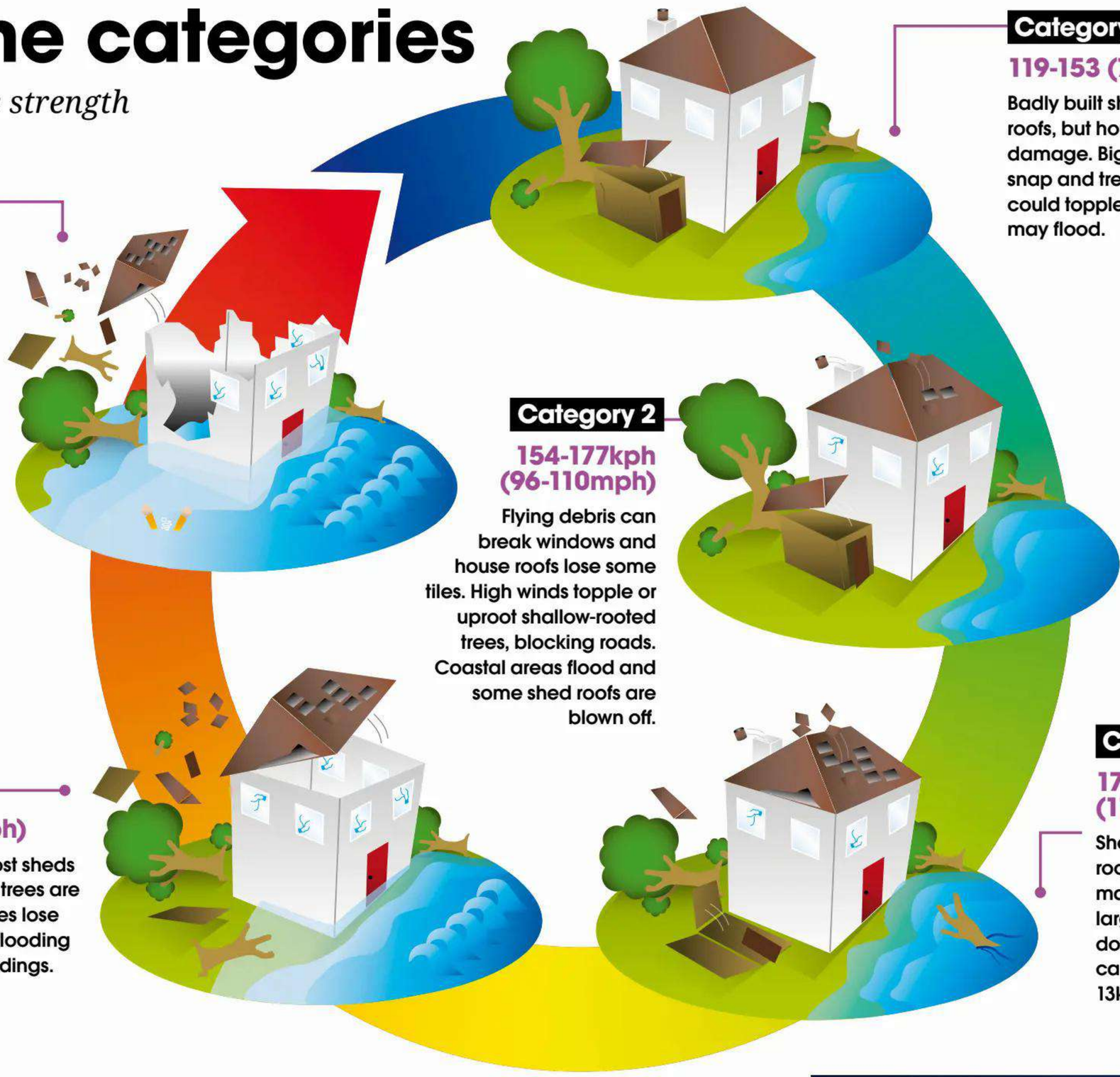
Similar processes drive supercells, hurricanes and brief summer thunderstorms. Thunderstorms start when wet unstable air is given a sustained upward 'nudge'. Air is unstable when it carries on rising or sinking when 'nudged' upwards or downwards, typically because it's warmer than the air above it.

Unstable air strongly forced upwards can rise long distances into the atmosphere to form ominous, towering thunderclouds. These tall clouds are critical for generating the torrential rain produced by ordinary thunderstorms and super storms.

Air has further to rise to the tops of tall clouds. As air rises, it cools and can hold less water. Eventually, this water comes out of the air to

Hurricane categories

Measuring a storm's strength



Category 1

119-153 (74-95mph)

Badly built sheds can lose their roofs, but houses suffer little damage. Big tree branches can snap and trees with shallow roots could topple over. Coastal roads may flood.

Category 2

154-177kph (96-110mph)

Flying debris can break windows and house roofs lose some tiles. High winds topple or uproot shallow-rooted trees, blocking roads. Coastal areas flood and some shed roofs are blown off.

Category 3

178-209kph (111-130mph)

Sheds collapse. House roofs and windows suffer major damage and large trees are blown down. Coastal flooding can spread more than 13km (8mi) inland.

Category 4

210-249kph (131-155mph)

Windblown debris fills the air. Most sheds are completely destroyed, most trees are snapped or uprooted, and houses lose their roofs. Widespread coastal flooding damages the lower floors of buildings.

Category 5

+249kph (+155mph)

Walls collapse, destroying homes. The lower floors of coastal houses suffer massive damage. People may need to be evacuated from low-lying houses up to ten miles inland.

form cloud droplets. Taller clouds therefore wring out more moisture. As the water droplets or ice crystals fall through the cloud, they collide and join together. Taller clouds mean a longer fall, more collisions and the potential for heavier rain.

All this rising air has to go somewhere and, in thundershowers, it sinks down the way that it came. Summer thunderstorms fizzle out in under an hour because the updraft – rising air – is smothered by this downdraft.

Thunderstorms become almost living entities that run by themselves when wind speed and direction changes with height. The downdraft returns to Earth in a different place from the updraft and spreads out on the surface. This cold air meets warmer air rushing into the updraft and forces it upwards to create a new updraft, called a thunderstorm 'cell'.

A supercell storm is born when the wind shear – changes in wind direction with height – is strong enough to cause a cell to become a rapidly spinning tube. This tube – called a mesocyclone – is the supercell's tornado generator.

Supercell storms and tornadoes occur in many places, but some – such as 'Tornado Alley' on the US Great Plains – are perfectly primed for super storms. During the spring and early summer, three air masses meet over the relatively flat plains, setting up intense wind shear.

Hot, dry air from the Mexican deserts acts as a lid preventing warm, moist air from the Gulf of Mexico rising through cold, dry air descending from the Rockies. When the warm, moist air manages to punch through the lid, it surges upwards, rapidly releasing its energy to fuel violent storms.

Hurricanes are also fuelled by warm, wet air rising during the summer. But they grow over hot ocean waters at least 27 degrees Celsius (80.6 degrees Fahrenheit) – not land. When hurricanes hit land or move over colder waters, they begin to weaken.

African easterly waves – areas of low air pressure that create clusters of thunderstorms – often act as seeds for hurricane growth. Provided the weather stays reasonably constant, the thunderstorms grow over the warm ocean. As the hot, wet air rises and cools, it releases vast amounts of water. This release then generates heat, which

The eyewall of Hurricane Katrina

encourages more air to rise and increases wind speeds.

The Earth's spin and growing wind speeds cause the thunderstorm cluster to start rotating. As it moves across the ocean and grows, it spins faster. Like bubbles swirling down a sink, individual thunderstorms stretch into spiral bands – rainbands – around the centre of rotation.

Water and bubbles going down a plughole tend to form a tube, with the faster flow near the drain. The growing hurricane system is similar – the strongest winds and rain are near the centre in a system of towering thunderstorms called the eyewall. The calm eye of the storm corresponds to the core of the tube – directly above the plughole.

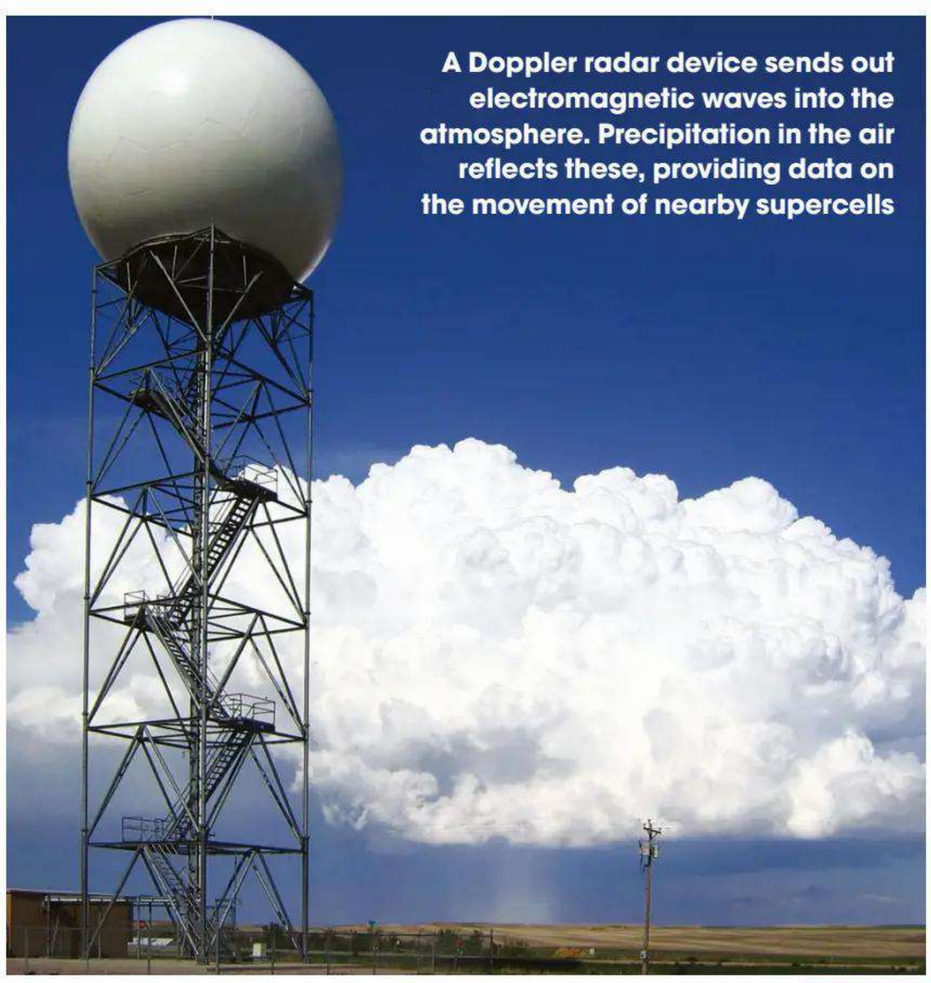
© Science Photo Library, US Gov

How storm supercells form

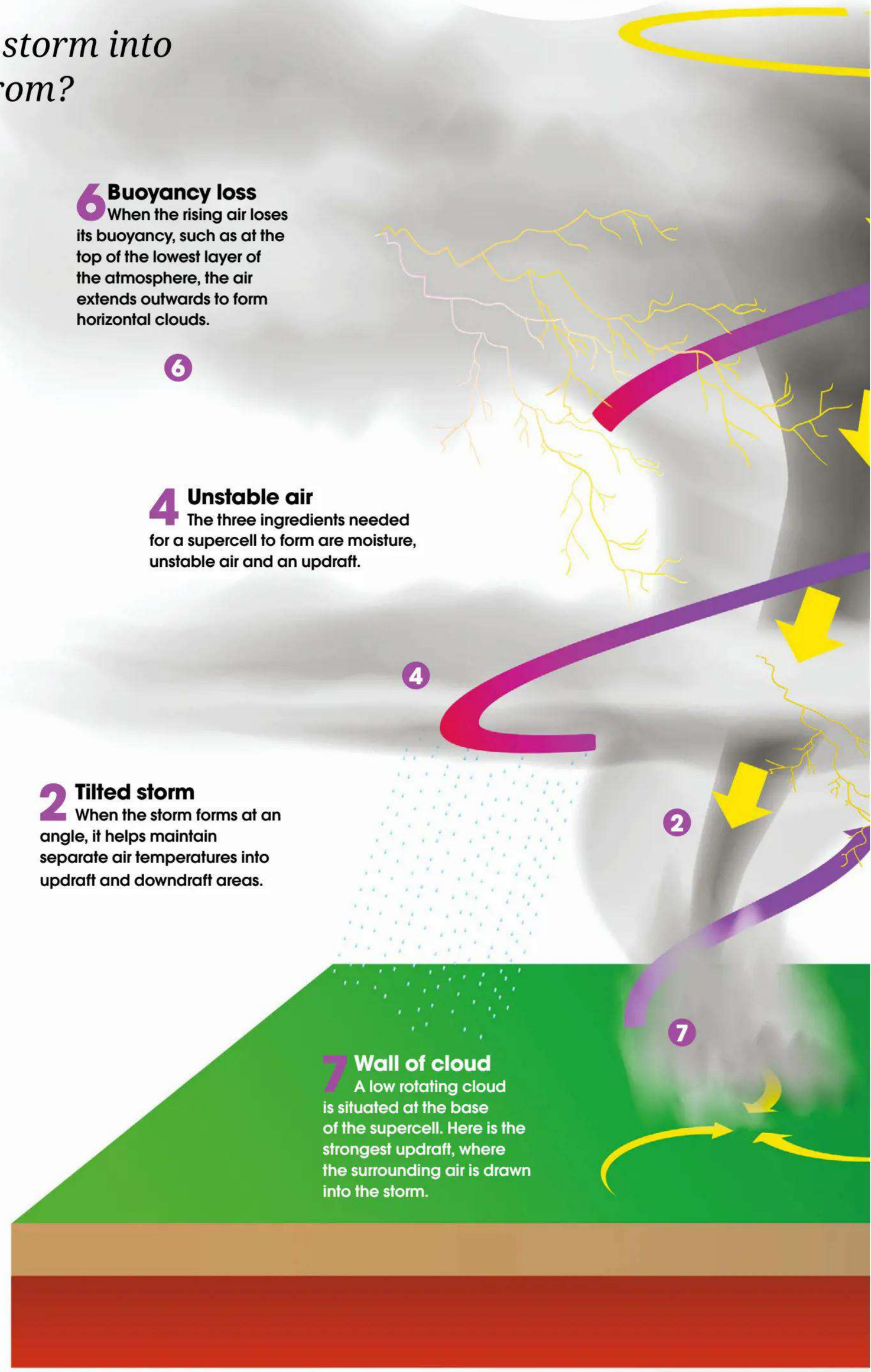
What turns an ordinary storm into a whirling maelstrom?

On a stormy day, if you can see a towering rod of clouds topped with a funnel-shaped horizontal cloud, there's a chance you are looking at a supercell. What separates supercells from regular thunderstorms is the rotating movement of air at the centre as it's drawn upwards to the top of the storm. Supercells are the least common form of thunderstorm. To spot a supercell in the distance, you need to observe the shape and movement of the clouds decorating them.

The most important factor that causes a supercell to form is wind shear. Wind shear is conflicting wind direction and speed that stops the air travelling smoothly straight across Earth's surface. The force of wind shear manipulates this movement into a rotating cycle. The strong winds, giant hailstones and potential to form tornadoes can make supercells a very destructive form of weather. They're most common in the central plains of the US and regularly occur during the spring season. Knowing what combination of factors form a supercell can help you stay safe and prepared for changing weather. Today, emergency services can send wireless alerts to everyone in an affected area when a severe supercell or tornado is due to pass through the region.

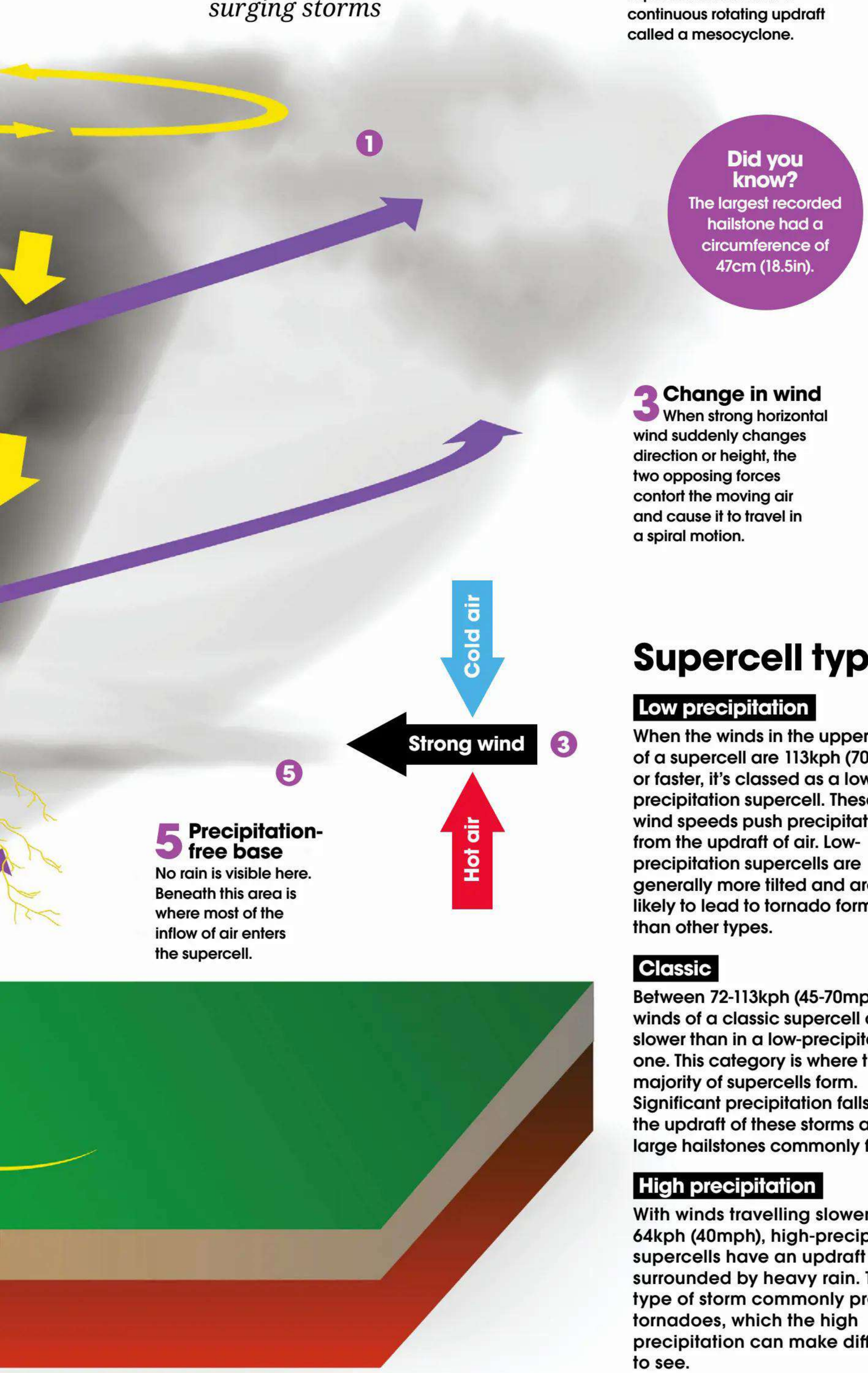


A Doppler radar device sends out electromagnetic waves into the atmosphere. Precipitation in the air reflects these, providing data on the movement of nearby supercells



Supercell structure

Explore the anatomy of these surging storms



1 Mesocyclone
A storm is classed as a supercell when it has a continuous rotating updraft called a mesocyclone.

Did you know?
The largest recorded hailstone had a circumference of 47cm (18.5in).

3 Change in wind
When strong horizontal wind suddenly changes direction or height, the two opposing forces contort the moving air and cause it to travel in a spiral motion.

5 Precipitation-free base
No rain is visible here. Beneath this area is where most of the inflow of air enters the supercell.

Supercell types

Low precipitation
When the winds in the upper level of a supercell are 113kph (70mph) or faster, it's classed as a low-precipitation supercell. These high wind speeds push precipitation far from the updraft of air. Low-precipitation supercells are generally more tilted and are less likely to lead to tornado formation than other types.

Classic
Between 72-113kph (45-70mph), the winds of a classic supercell are slower than in a low-precipitation one. This category is where the majority of supercells form. Significant precipitation falls next to the updraft of these storms and large hailstones commonly form.

High precipitation
With winds travelling slower than 64kph (40mph), high-precipitation supercells have an updraft that's surrounded by heavy rain. This type of storm commonly produces tornadoes, which the high precipitation can make difficult to see.

Creating tornadoes

Although many rotating storms may look like tornadoes, only some supercells transition into them. Tornadoes need a specific set of conditions to form. As they are defined as rotating air columns that make contact with Earth's surface and a thundercloud, tornadoes require the air of a supercell to spin very close to the ground in order to form. For this to occur, warm air needs to rise above the cool air at a higher altitude, which then needs to drop down to the surface enough to push the air out horizontally in gusts of wind. When this happens continuously, the air at the ground will start to spin, just as it does further up in the atmosphere in a supercell. Not all supercells that form near the ground result in tornadoes. If the air is rotating too slowly, the tornado structure will not form, while if the air is too cold near the ground, it will dissipate away from the storm's centre.

A typical tornado's damage path is around 1.9-3km (1.2 -1.8mi)

© Alamy / Getty / Shutterstock

EXTREME WEATHER

Hunting hurricanes

What are hurricanes and how can we tell when they're coming?

Hurricanes are some of the strongest and most dangerous weather events on the planet. Between 2000 and 2020, they claimed the lives of 2,137 people in the US alone. These rotating thunderstorms are relentless, taking days to pick a path through towns and cities before burning out. Each one can measure 483 kilometres (300 miles) from end to end and stretch 15 kilometres (9.5 miles) into the sky. And they all have winds in excess of 119 kilometres per hour (74 miles per hour) – the Labor Day hurricane of 1935 topped out at 298 kilometres per hour (185 miles per hour).

The ability to predict storms has changed the world. People in hurricane-prone areas now receive warnings days before deadly winds arrive. But it's not an exact science. One tiny change can cause a dramatic difference in their behaviour. It's up to organisations like the National Oceanic and Atmospheric Administration (NOAA) to plot the path each tropical storm will take and make sure everyone has time to get to safety.

Hurricanes are not the only type of spinning weather system. They belong to a group of storms called tropical cyclones. The word 'hurricane' describes the strongest of the cyclones in the North Atlantic, central North Pacific and eastern North Pacific Oceans. In the Northwest Pacific, the same strong weather systems are called typhoons, and in the South Pacific and Indian Ocean they are all known as 'tropical cyclones', regardless of their strength. Tornadoes are a different type of weather entirely. They are much smaller than hurricanes and form over land, not water. They tend to last just a few minutes and don't travel nearly as far.

A hurricane is different to a waterspout, which is a tornado that forms over water.

Great Galveston hurricane

On 8 September 1900, the biggest city in Texas was flattened by a hurricane. Forecasters had warned of a tropical storm south of Florida two days earlier, but they thought it was moving northward. Unknown to them, it was actually turning west into the Gulf of Mexico and rapidly growing in strength. Ships had noticed the disturbance, but had found it hard to get messages back to shore. The weather was worsening, and the tide was rising, but by the time the local weather bureau started warning people to leave, it was already too late. Winds had picked up to 225kph (140mph) and waves were towering 4.5m (14.8ft) into the air. It wasn't the strongest hurricane ever to hit the US, but was by far the deadliest. It claimed the lives of around 8,000 people.

This pressure map shows the Galveston hurricane just before it came ashore

Anatomy of a hurricane

As hot air rises from the oceans near the equator, a storm can start to spin

It's not uncommon for storms to stack up back to back during hurricane season.

1 Air rushes in
High-pressure air moves through the eye of the storm.

2 Eye of the storm
The centre of the storm is still and calm while air rotates around the outside.

3 The eyewall
A fast-moving wall of cloud surrounds the eye of the storm.

4 Hot air rising
Air rises from the surface of the sea, leaving empty space behind.

5 Warm water
Hurricanes feed on the warm, damp air that evaporates from tropical oceans.

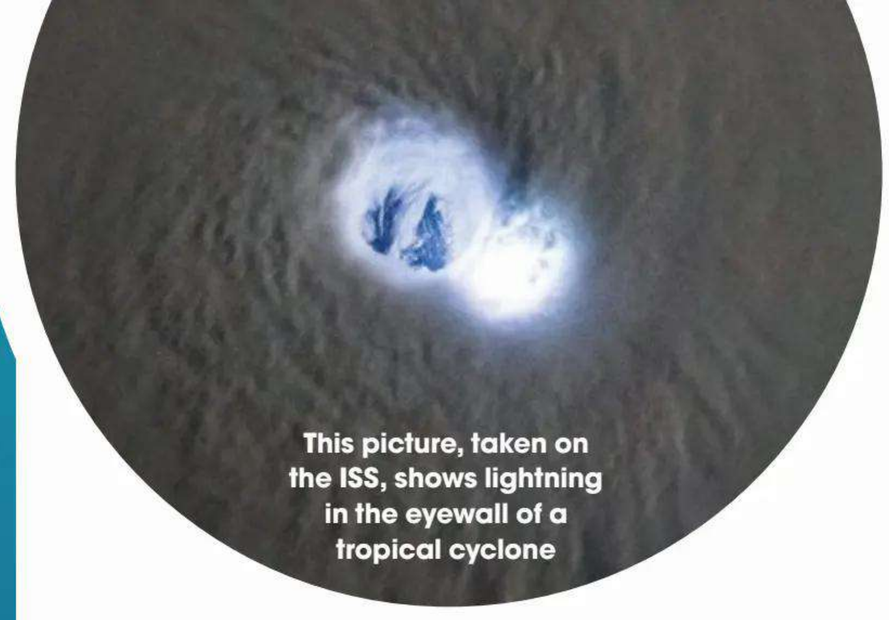
8 Spin
Air curves over the Earth's surface as it moves through the storm, setting the whole system into a spin.

The making of a hurricane

To cook up a perfect storm you need: warm water, wet air, slow winds high in the atmosphere and a cluster of thunderclouds. Hurricanes often start out as small storms off the coast of Africa. Known as 'tropical depressions', these embryonic cyclones move west, picking up strength as they cross the Atlantic. They can only grow when the temperature of the water exceeds 27 degrees Celsius (80.6 Fahrenheit), and this is only at certain times of year. In the Atlantic, hurricane season runs from 1 June to 30 November. In the eastern Pacific it starts about two weeks earlier.

When the water is warm, it starts to evaporate, making the air wet. The vapour rises into the atmosphere, and if the wind is calm it condenses to form clouds. If the air moves too quickly, the top of the developing storm simply blows away. But if conditions are right it starts to draw more air upwards, like a plug hole draws water from a bath. Just like a plug hole, the air entering the storm starts to spin.

The spin of a hurricane is down to the Coriolis effect. Earth, as we know, is a spinning ball. Every point on its surface takes 24 hours to complete a rotation. This means that the points on the equator move much faster than the points on each of the poles. And this means that winds travelling over Earth's surface don't go in a straight line. In the Northern Hemisphere they bend off to the right, and in the Southern Hemisphere they bend left, which is why hurricanes always spin in the same direction.


This picture, taken on the ISS, shows lightning in the eyewall of a tropical cyclone

Evolution of Hurricane Ian

Hurricane Ian battered Cuba and the East Coast of the US in September 2022

1 Tropical storm
Hurricane Ian started as a tropical disturbance in the Atlantic Ocean before moving west into the Caribbean Sea.

2 Category 1-3 hurricane
The storm moved north over Cuba, becoming a category 1, 2 and then 3, with wind speeds over 205kph (125mph).

3 Category 4 hurricane
By the time Ian made landfall in Florida, it was a category 4 hurricane with wind speeds in excess of 241kph (150mph).

4 Category 1 hurricane
As the storm moved north towards Charleston, it weakened first to a category 1 and then a tropical storm.

But just because the winds twist in a predictable way doesn't mean that the storms are easy to forecast. Of the hundreds of storms that roll towards the US each year, only around 29 gain enough strength to get names, 15 reach wind speeds high enough to become hurricanes and seven become major hurricanes.

It's the job of the National Hurricane Center (NHC) to keep track of them all. The Hurricane Specialist Unit keeps a constant watch over the Atlantic and the Eastern North Pacific oceans. Satellites orbit the world from top to tail twice every day, taking pictures, measuring the temperature and tracking the moisture in the air. If anything looks suspicious, the NHC sends in the hurricane hunters, This elite team of planes and pilots specialise in chasing storms. They fly right into the wind to gather measurements. It might sound dangerous, but the risk of damage to the aircraft is low. Meteorologists use the data to predict what a storm might do next. It's not an exact science, so the NHC repeats the process every few hours, adjusting its forecasts as each storm evolves.

Natural warning signs

The sea swells

As a hurricane approaches, the sea starts to get rougher. This can happen days before landfall. Waves rise, lifting to heights of 2m (6.6ft) or more.

The clouds change shape

Hot air rising from the sea carries water into the sky, forming distinctive clouds. Cirrocumulus clouds look like ripples.

Animals hide

Many animals sense changes in air pressure before a storm. In the sea, sharks, dolphins and lobsters move to deeper water.

© Getty / NOAA / International Space Station Expedition 42 crew / NASA Earth Observatory image by Jesse Allen, using VIIRS data from the Suomi National Polar-orbiting Partnership

Are hurricanes getting stronger?

As Earth's climate changes, extreme weather is too

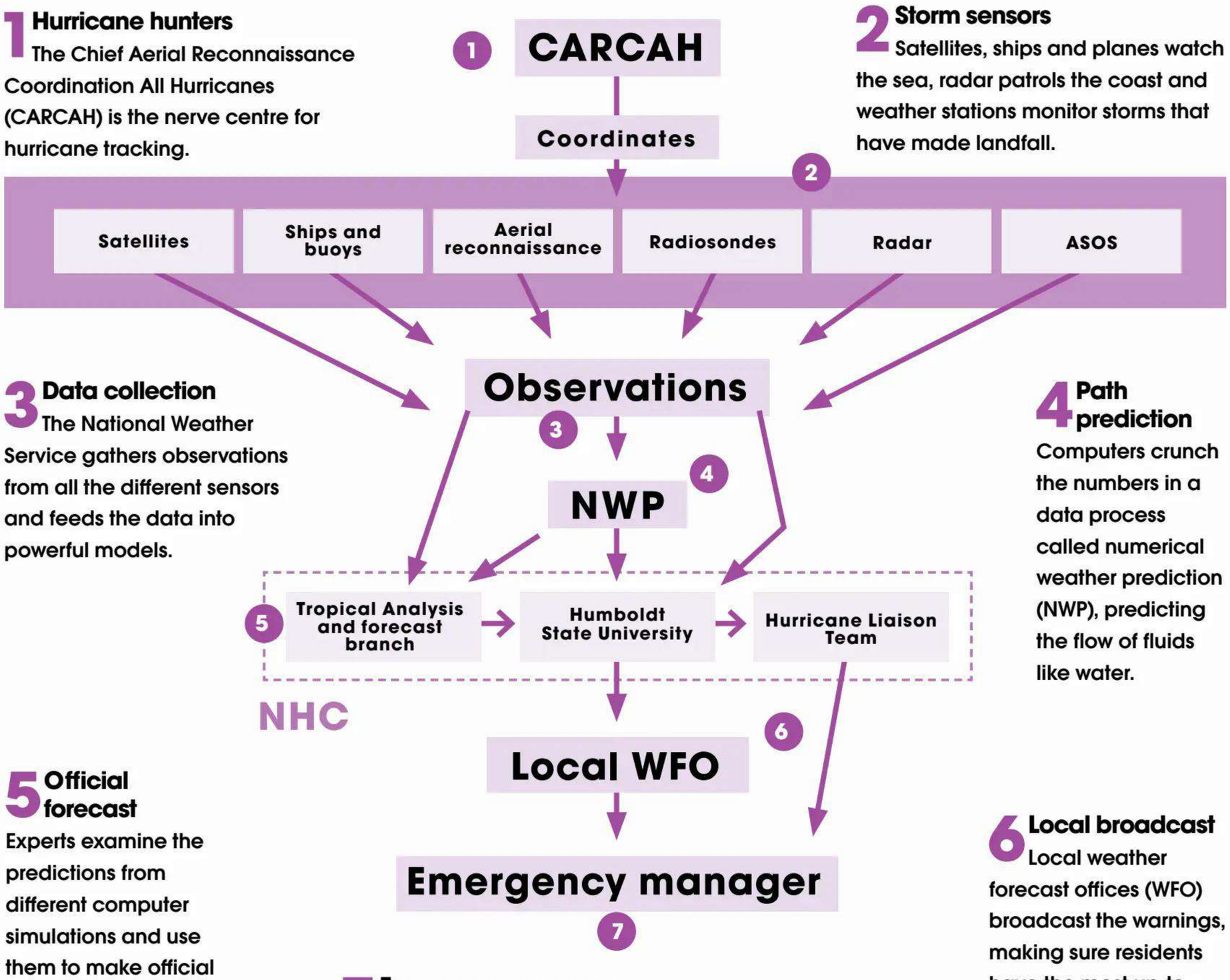
There's no doubt that our climate is changing – NASA says the evidence is unequivocal. Current warming is happening faster than at any other time in the past 10,000 years. But the effect a warmer world will have on hurricanes is hard to predict. Rising global temperatures are likely to impact hurricanes because tropical cyclones feed on warm, wet air. But the complex nature of these storms makes it impossible to know exactly how they'll change over time. On average, the evidence suggests that hurricanes are likely to become more frequent and more dangerous. As the world gets warmer, the air will get wetter, and wetter air means heavier rain. It's chemistry: the hotter it is, the more evaporation there will be. Storm-induced flooding will also be more likely as ice sheets melt and the sea expands.

Predicting hurricanes

How does the National Hurricane Center keep track of incoming storms?

1 Hurricane hunters
The Chief Aerial Reconnaissance Coordination All Hurricanes (CARCAH) is the nerve centre for hurricane tracking.

2 Storm sensors
Satellites, ships and planes watch the sea, radar patrols the coast and weather stations monitor storms that have made landfall.



3 Data collection
The National Weather Service gathers observations from all the different sensors and feeds the data into powerful models.

4 Path prediction
Computers crunch the numbers in a data process called numerical weather prediction (NWP), predicting the flow of fluids like water.

5 Official forecast
Experts examine the predictions from different computer simulations and use them to make official forecasts every two to six hours.

6 Local broadcast
Local weather forecast offices (WFO) broadcast the warnings, making sure residents have the most up-to-date information for their area.

7 Emergency response
Emergency managers coordinate with local weather offices and the National Hurricane Center to decide if and when to evacuate.

5 Facts Weathering the storm

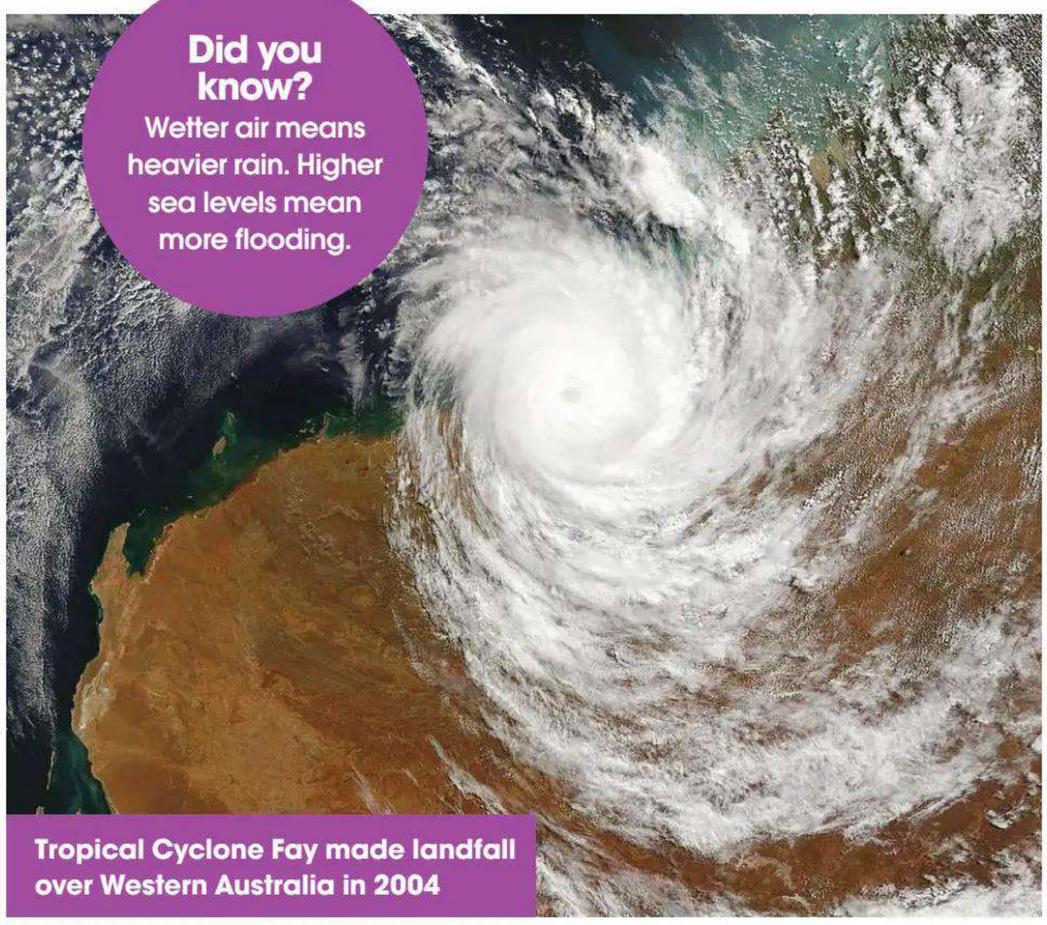
1 Stock up
It's recommended to stock up on emergency supplies in advance of the hurricane season. The list includes food, water, medicine, torches, batteries, important documents and a fire extinguisher.

2 Wind-proof your home
The Red Cross Hurricane Safety Checklist suggests protecting homes by removing or anchoring loose objects in the garden, covering the windows with storm shutters and trimming nearby trees.

3 Stay informed
The Federal Emergency Management Agency recommends signing up to local alerts. The National Weather Service gives each storm a warning level: yellow advisory, amber watch and red warning.

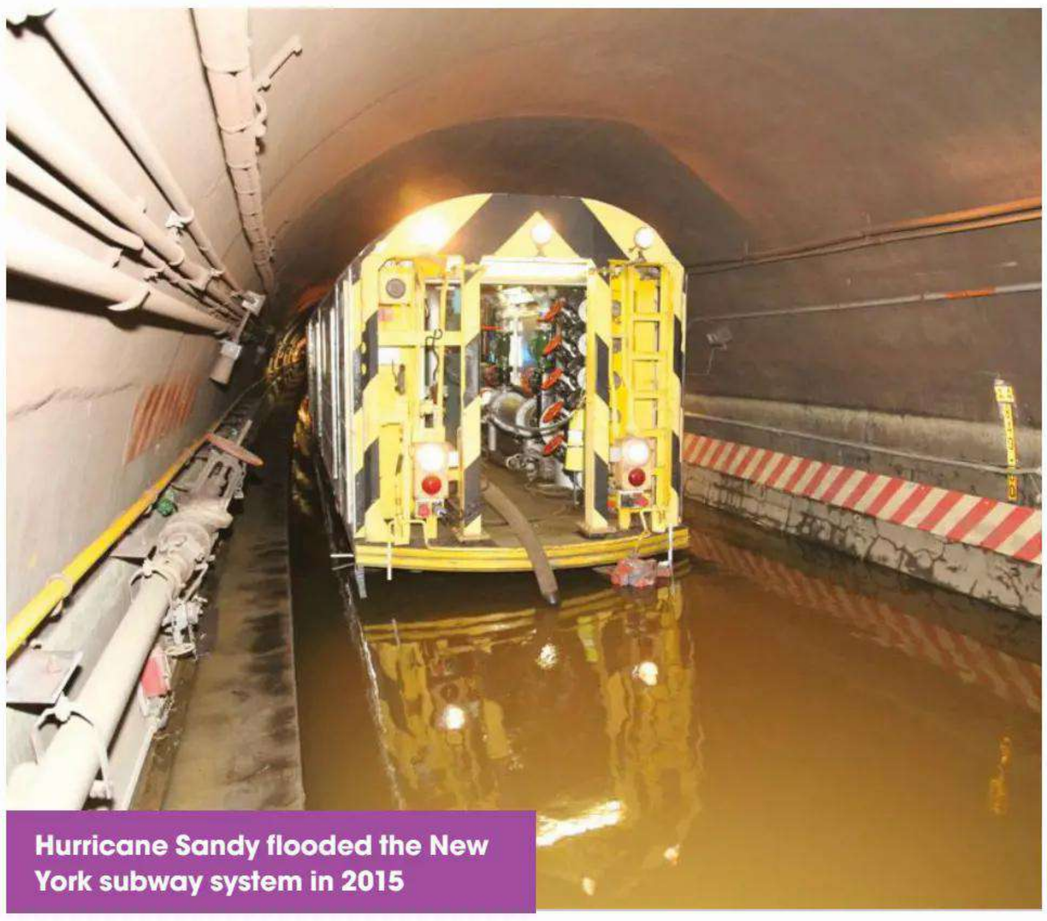
4 Take an inventory
The Insurance Information Institute suggests taking an inventory before hurricane season. This makes it easier to claim disaster aid or an insurance payout if anything is damaged.

5 Make a plan
NOAA suggests making an emergency plan with friends and family. It helps decide in advance where to go, what to take and how to get there.

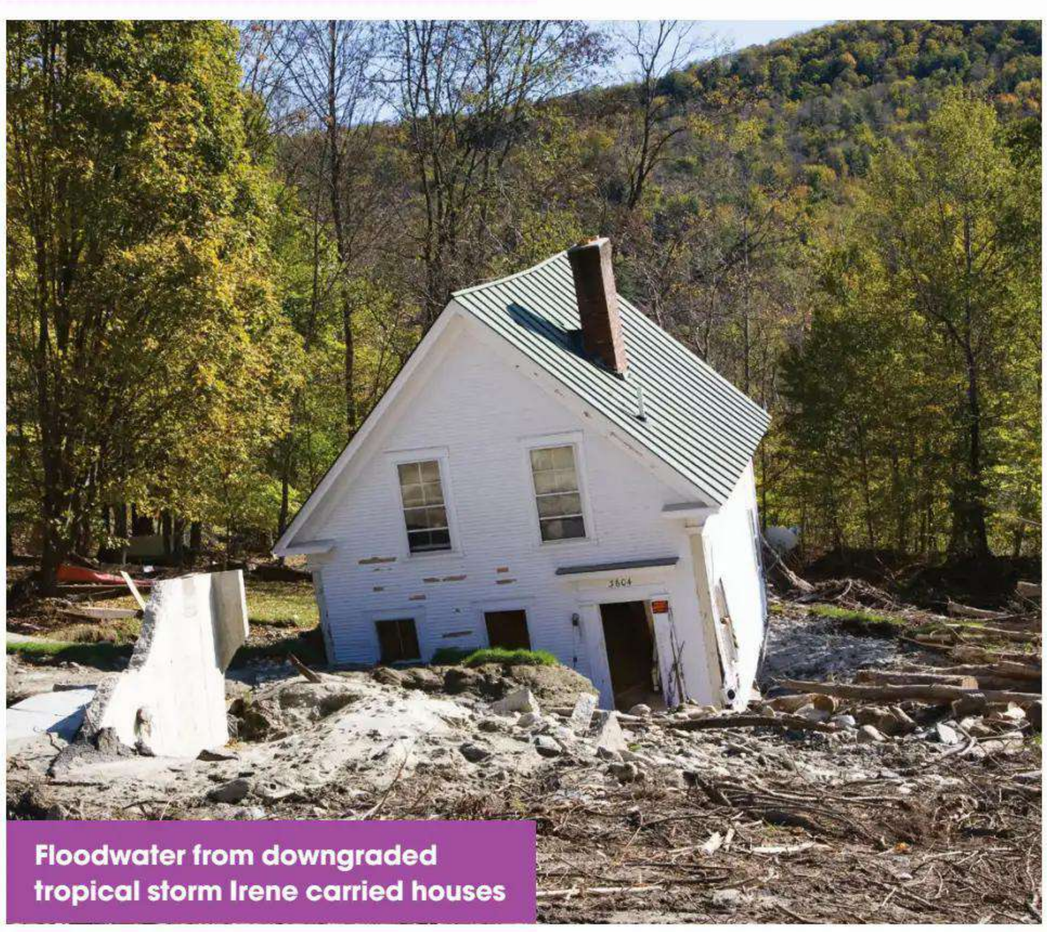


Did you know?
Wetter air means heavier rain. Higher sea levels mean more flooding.

Tropical Cyclone Fay made landfall over Western Australia in 2004



Hurricane Sandy flooded the New York subway system in 2015



Floodwater from downgraded tropical storm Irene carried houses

Interview with a hurricane scientist

Dr Jordan J. Gerth, a physical scientist at the National Oceanic and Atmospheric Administration (NOAA), talks to us about using satellites for hurricane forecasting

How much has satellite technology changed hurricane forecasting?

It's hard to imagine hurricane forecasting without the use of satellites. Satellites are a primary tool to track storms and monitor their intensity over the ocean. Without them our only indication would be buoys and ships, and there would still be a substantial number of storms that would be a surprise upon landfall, of great consequence to the people that live along the coasts.

How much does NOAA rely on satellite data?

Satellites are fundamental to NOAA's mission and our ability to predict the weather. NOAA runs sophisticated computer models that use satellite data as a primary input for weather conditions around the world. Satellites provide over 90 per cent of the input to these. Without fully knowing global weather conditions, it's difficult to make local predictions and warnings.

Are there ever times when satellites are suggesting one thing, but experience and instincts suggest otherwise?

Satellites provide critical observations and meteorologists are trained to not look beyond the data. However, sometimes despite all of our advances in weather prediction, internal storm dynamics are difficult to immediately ascertain with the data that's available. In those cases, the National Weather Service has to rely on rigorous training, expertise of colleagues and computer simulations to provide the best forecast.

Are there still technological advances on the horizon that could improve hurricane forecasting even further?

Yes! NOAA established the Hurricane Forecast Improvement Program (HFIP) after devastating hurricanes in 2004 and 2005, such as Katrina, to improve the accuracy, and therefore Americans' confidence, in hurricane forecasts. Recently, HFIP is leading to the development of a Hurricane Analysis and Forecast System to improve hurricane forecasts with advancements in computer models. NOAA is also planning future satellite missions that include enhanced capabilities for monitoring hurricanes and funding research projects to collect additional data with hurricane hunter aircraft.

Will it get easier or harder to predict hurricanes as the climate changes?

Climate change is unlikely to change the predictability of hurricanes, but it may lead to stronger hurricanes. Hurricanes typically increase in intensity under low wind shear around the storm and warm water temperatures. Under a changing climate, there's evidence that water temperatures will be on the increase.

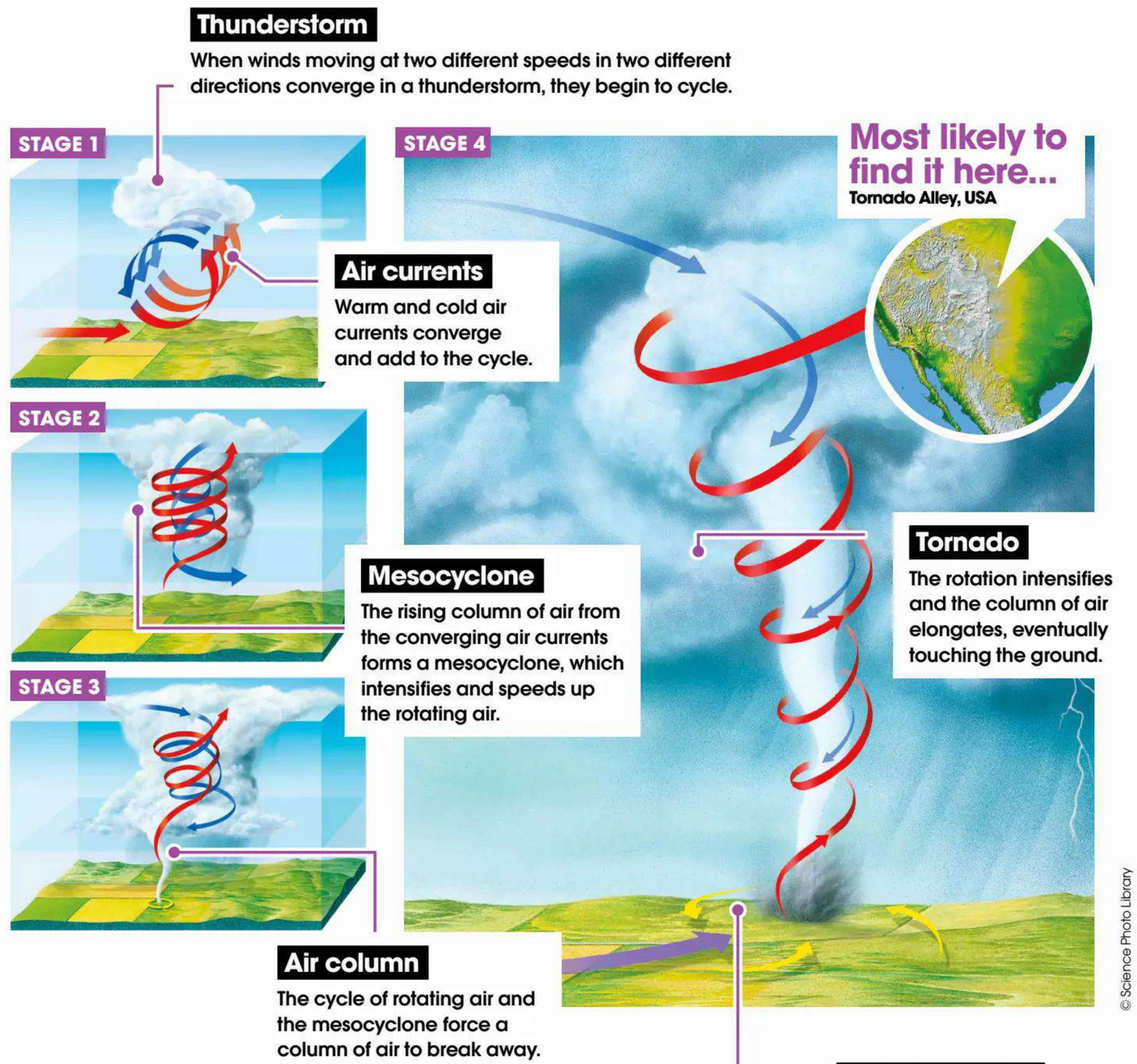
© NASA / U.S. Fish and Wildlife Service - Northeast Region / Metropolitan Transportation Authority of the State of New York / American Meteorological Society

Tornadoes

How these destructive columns of rotating air form

These storms are some of nature's biggest killers – rotating, violent columns of air that touch both the clouds and the earth. Most tornadoes look like funnels, with the narrow end making contact with the ground. They can have wind speeds of up to 480 kilometres per hour (300 miles per hour) and be dozens of kilometres/miles wide. Most tornadoes travel across the ground for a short distance before breaking up, but not before they cause considerable damage. The United States experiences the majority of the world's tornadoes in the summer, although they have been seen on every continent but Antarctica.

Tornadoes can easily remove entire houses and bridges, shredding and twisting them into pieces. On the Enhanced Fujita Scale, the weakest (or EF1) tornadoes are very short-lived, where the most violent (EF5) can completely shred buildings and strip asphalt from road beds. People can die in any type of tornado if they don't have adequate shelter, but EF5 tornadoes – of which there are fewer than one per cent on average – have the most fatalities.



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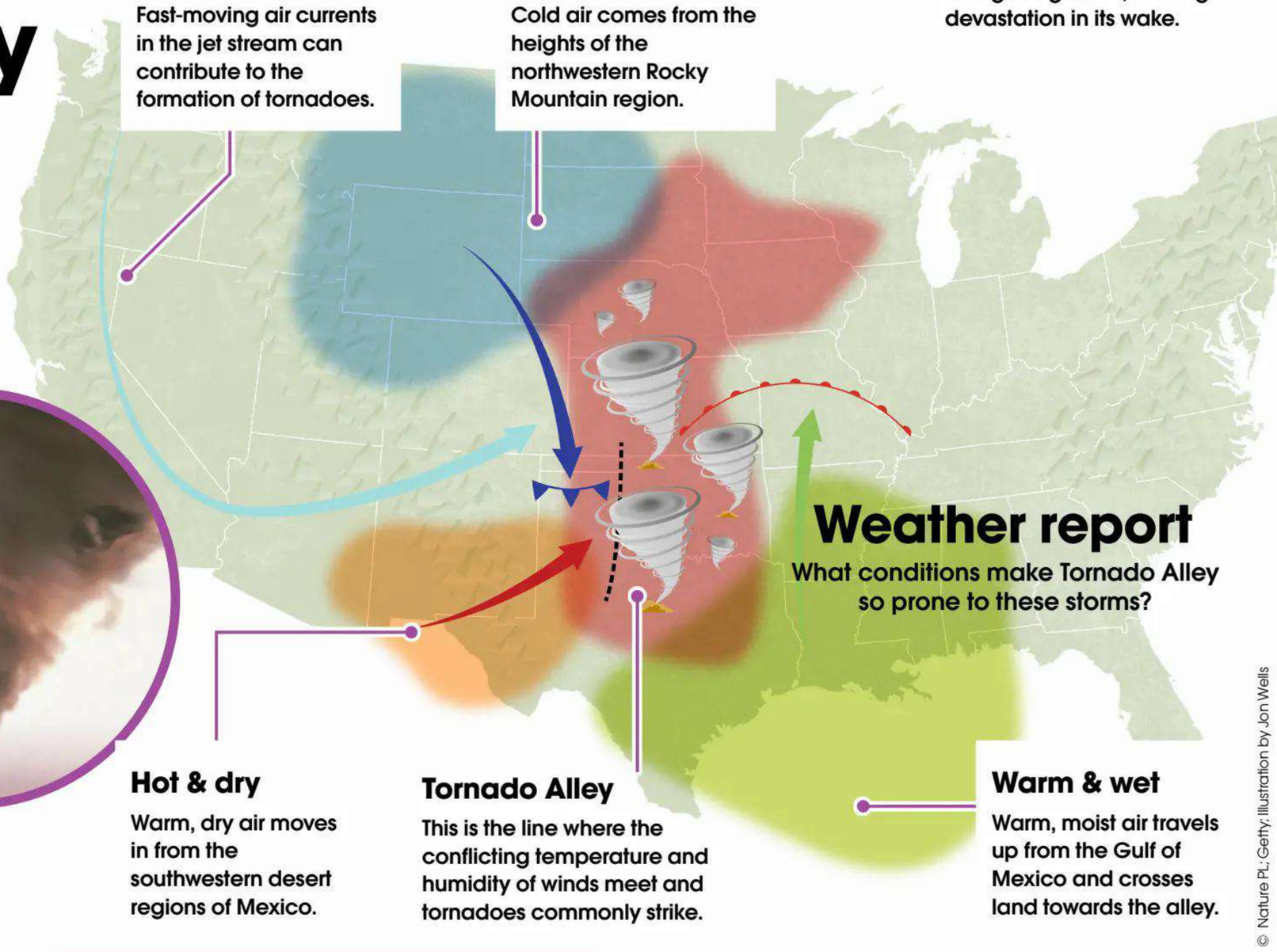
Tornado Alley

Discover the region of the US tormented by tornadoes

Certain conditions have been observed to promote a tornado's formation, including contrasting temperatures and humidity. One region in the US offers such perfect conditions that it's become a hot spot.

Along the Great Plains a stretch of land crossing states such as Kansas and Oklahoma forms Tornado Alley. This is where weather fronts of different temperatures can converge. Warm, humid winds from the Gulf of Mexico, for example, can crash with the cool dry air rolling in from the Rocky Mountains in the west.



© Nature PL; Getty; Illustration by Jon Wells

How are blizzards created?

These deadly winter storms can strike without warning

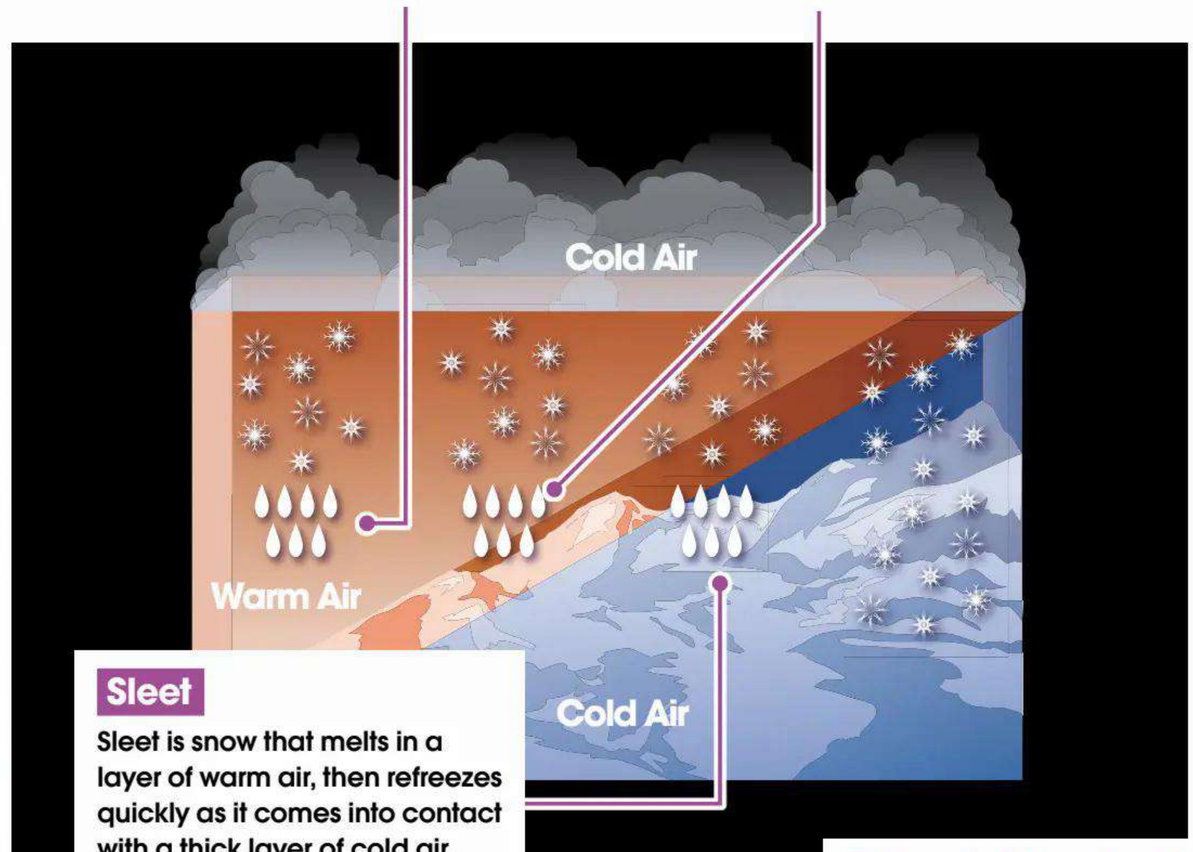
In January 1996, 100 million tons of snow fell on the streets of New York City and nearby Philadelphia was buried under a record 78 centimetres (30.7 inches). Ice storms and sub-zero temperatures stretched as far south as sunny Florida, trapping people in their homes, often without electricity. In 1891, easterly winds dumped 3.6 metres (11 feet) of snow in London. Trains were completely buried under tremendous drifts and 65 ships sank under the heavy ice and snow.

Blizzards form exactly like thunderstorms. A cold front pushes warmer, moist air into the atmosphere, condensing into clouds. If temperatures stay below freezing, snow falls instead of rain. If huge amounts of snow are accompanied by gale-force winds, it's possible to achieve a complete whiteout, when earth and sky merge in a disorienting canvas of white.

Did you know?
For a winter storm to qualify as a blizzard, there must be sustained winds of at least 58kph (35mph) and less than 0.4km (0.25mi) visibility for three hours or more.

Ice storms

Extreme ice storms can bring down power lines and also burst pipes, leaving people without basic utilities for weeks



Rain
What kind of precipitation you end up with all depends on the air temperature as it is falling. When the lowest layer of air is warm, it falls as snow but melts into rain.

Freezing rain
This occurs when precipitation falls between a layer of warm air between two layers of cold air. It melts when it reaches the warm layer, then freezes when it hits a thin layer of cold air.

Sleet
Sleet is snow that melts in a layer of warm air, then refreezes quickly as it comes into contact with a thick layer of cold air.

Ice storms are the most dangerous of winter storms. They occur when there are two layers of cold air sandwiching a layer of warm air. Rain falls through one cold layer and freezes, falls through the warm layer and melts completely, then hits the second cold layer. Its temperature drops below freezing, but the rain does not actually freeze until it hits the frozen ground. These storms can leave a smooth layer of ice on anything below freezing. Ice on roads is treacherous, and its weight also causes tree branches to fall, blocking roads and bringing down power lines – sometimes the ice alone is enough. Water inside pipes can freeze and burst, causing serious plumbing issues. Death is often caused by carbon monoxide poisoning as people use generators and other heat sources. Ice storms are common in the northeastern United States although they occur in Canada and Europe as well.

Most likely to find it here...
Albany, New York

Firestorms

From tornado-force winds to superhot flames, dare you discover nature's most violent infernos?

Did you know?
Large wildfires have increased decade by decade in western USA since the mid-Eighties.

Firestorms are among nature's most violent and unpredictable phenomena. Tornado-force winds sweep superhot flames of up to 1,000 degrees Celsius (1,832 degrees Fahrenheit) through buildings and forests alike. Victims often suffocate before they can flee and entire towns can be obliterated. Survivors of firestorms describe darkness, 100-metre (330-foot)-high fireballs and a roaring like a jumbo jet. To give you an idea of the sheer heat, firestorms can be hot enough to melt aluminium and tarmac, warp copper and even turn sand into glass.

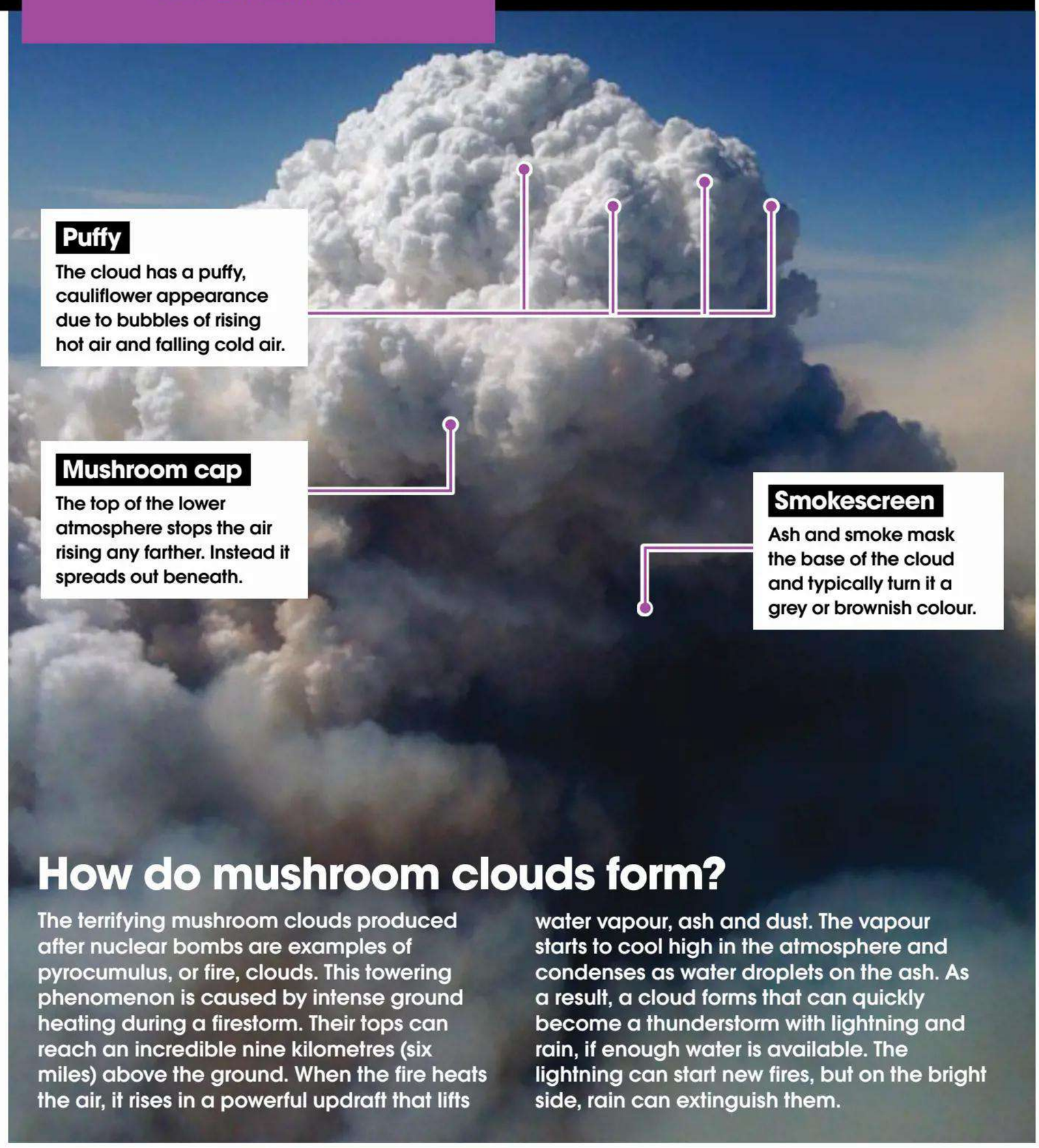
Firestorms happen worldwide, especially in the forests of the United States and Indonesia, and in the Australian bush. They occur mostly in summer and autumn when vegetation is tinder dry. Although they are a natural phenomenon, among the most devastating were triggered deliberately. During World War II, for instance, Allied forces used incendiaries and explosives to create devastating firestorms in Japanese and German cities. Firestorms also erupted after the cataclysmic meteor impact of 66 million years ago that many believe to have triggered the extinction of the dinosaurs.

Climate change may be already increasing the risk of mega-fires by making summers ever hotter and drier. The Rocky Mountain Climate Organization, for example, reported that from 2003 to 2007, the 11 western US states warmed by an average of one degree Celsius (1.8 degrees Fahrenheit). The fire danger season has gone up by a staggering 78 days since 1986.

The risk of an Australian firestorm striking a major city has also heightened in the last 40 years. Climate change may have exacerbated this by increasing the risk of long heat waves and extremely hot days. In January 2013 alone, a hundred bushfires raged through the states of New South Wales, Victoria and Tasmania following a record-breaking heat wave. Maximum daily temperatures rose to 40.3 degrees Celsius (104.5 degrees Fahrenheit), beating the previous record set in 1972.

Firestorms can happen during bush or forest fires, but are not simply wildfires. Indeed, a firestorm is massive enough to create its own weather (see boxout). The thunderstorms, powerful winds and fire whirls – mini tornadoes of spinning flames – it can spawn are all part of its terrifying power.

The intense fire can have as much energy as a thunderstorm. Hot air rises above it, sucking in additional oxygen and dry debris, which fuel and spread the fire. Winds can reach tornado speed –



How do mushroom clouds form?

The terrifying mushroom clouds produced after nuclear bombs are examples of pyrocumulus, or fire, clouds. This towering phenomenon is caused by intense ground heating during a firestorm. Their tops can reach an incredible nine kilometres (six miles) above the ground. When the fire heats the air, it rises in a powerful updraft that lifts water vapour, ash and dust. The vapour starts to cool high in the atmosphere and condenses as water droplets on the ash. As a result, a cloud forms that can quickly become a thunderstorm with lightning and rain, if enough water is available. The lightning can start new fires, but on the bright side, rain can extinguish them.

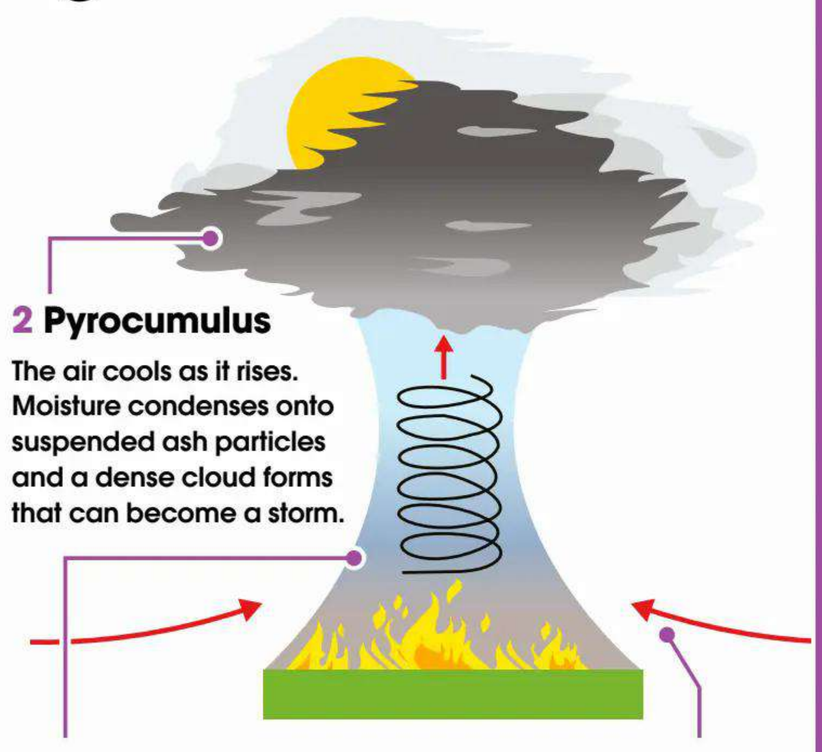
How firestorms change the weather

Firestorms can release as much energy as a lightning storm on a hot summer's afternoon.

Warm air above the fire is lighter than the surrounding air so it rises; the swirling pillar of lifting air above the fire is called a thermal column. This tornado-like structure is responsible for a firestorm's power. Under the right weather conditions, air can rise inside the column at eye-watering speeds of 270 kilometres (170 miles) per hour!

Cooler air gusts into the space left behind by the ascending air, causing violent winds that merge fires together into a single intense entity. They also blow in oxygen, wood and other flammable material that serve to fuel and intensify the blaze.

Turbulent air spiralling around the thermal column can spawn fire tornadoes and throw out sparks. These can set light to trees and houses tens of metres/feet away, increasing the conflagration's range.



tens of times the ambient wind speeds. The huge pillar of rising air – called a thermal column – swirling above the firestorm can generate thunderclouds and even lightning strikes that spark new fires.

The thermal column, in turn, can spawn a number of fiery tornadoes, which can tower to 200 metres (650 feet) and stretch 300 metres (980 feet) wide, lasting for at least 20 minutes. These fling flaming logs and other burning debris across the landscape, spreading the blaze. The turbulent air can gust at 160 kilometres (100 miles) per hour, scorching hillsides as far as 100 metres (330 feet) away from the main fire. It's far more powerful than a typical wildfire, which moves at around 23 kilometres (14.3 miles) per hour – just under the average human sprint speed.

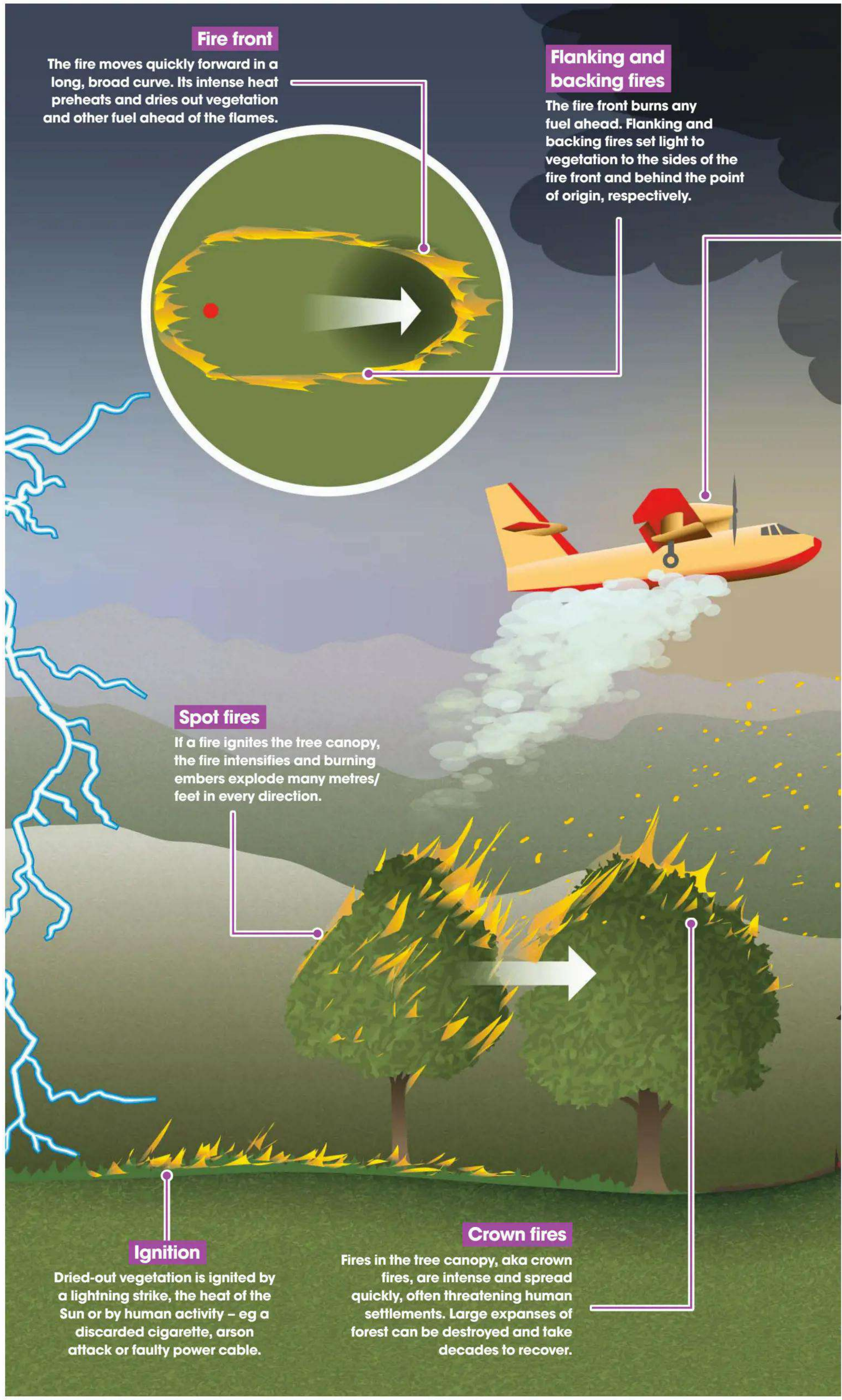
Like all fires, firestorms need three things to burn. First is a heat source for ignition and to dry fuel so it burns easier. Fuel, the second must, is anything that combusts, whether that be paper, grass or trees. Thirdly, all fires need at least 16 per cent oxygen to facilitate their chemical processes. When wood or other fuel burns, it reacts with oxygen in the surrounding air to release heat and generate smoke, embers and various gases. Firestorms are so intense that they often consume all available oxygen, suffocating those who try to take refuge in ditches, air-raid shelters or cellars.

Fighting firestorms

Fire wardens, air patrols and lookout stations all help detect fires early, before they can spread. Once a fire starts, helicopters and air tankers head to the scene. They spray thousands of gallons of water, foam or flame-retardant chemicals around the conflagration. In the meantime, firefighters descend by rope or parachute to clear nearby flammable material.

We can reduce the risk of fire breaking out in the first place by burning excess vegetation under controlled conditions. Surprisingly this can actually benefit certain plants and animals. Canadian lodgepole pines, for example, rely partly on fire to disperse their seeds. Burning also destroys diseased trees and opens up congested woodland to new grasses and shrubs, which provides grazing for cattle and deer.

Vegetation in fire-prone areas often recovers quickly from a blaze. Plants like Douglas fir, for instance, have fire-resistant bark – although it can only withstand so much heat. Forest owners help flora to return by spreading mulch, planting grass seed and erecting fences.



Cloud

The hot air cools as it goes up, and droplets of water condense on the ash particles. A puffy cloud forms with pockets of billowing, moist air.

Airtanker

Aerial firefighters dump water from above, or for more serious blazes, fire retardants like ammonium sulphate are used, which also act as a fertiliser to help promote regrowth.

Thermal column

Air is warmed by the fire, becomes lighter than the surrounding air and rises to create a thermal column. The lifting air carries smoke and ash from the blaze with it.

Wind

Sparks and embers flying off the tree canopy are blown with the breeze. They cause the fire to spread and advance in the direction of the wind.

Self-sustaining

Winds blow in towards the conflagration to replace the rising air. This brings oxygen to feed the fire. The thermal column becomes self-sustaining and a firestorm ensues.

Going up

Fires move faster uphill for several reasons: the flames are closer to fuel sources; vegetation is typically drier on slopes so easier to ignite; and winds often blow upslope because warm air rises.

Did you know?

The biggest humanmade firestorm took place in Dresden, Germany, in 1945; 70 per cent of the city was destroyed.

Firestorm step-by-step

See how a deadly firestorm starts as a single spark and spreads rapidly through the forest

Five mega firestorms

1 Black Saturday

In 2009, one of Australia's worst bushfires killed 173 people, injured 5,000 more, destroyed 2,029 homes, killed a great number of animals and burnt 4,500 square kilometres (1,700 square miles) of land. Temperatures may have reached 1,200 degrees Celsius (2,192 degrees Fahrenheit).

2 Great Peshtigo

The deadliest fire in American history claimed 1,200-2,500 lives, burned 4,860 square kilometres (1,875 square miles) of Wisconsin and upper Michigan and destroyed all but two buildings in Peshtigo in 1871.

3 Ash Wednesday

More than 100 fires swept across Victoria and South Australia on 16 February 1983, killing 75 people, destroying 3,000 homes and killing 50,000 sheep and cows. It was the worst firestorm in South Australia's history.

4 Hamburg

This firestorm brought on by an Allied bomb strike in 1943 killed an estimated 44,600 civilians, left many more homeless and levelled a 22-square-kilometre (8.5-square-mile) area of the German city. Hurricane-force winds of 240 kilometres (150 miles) per hour were raised.

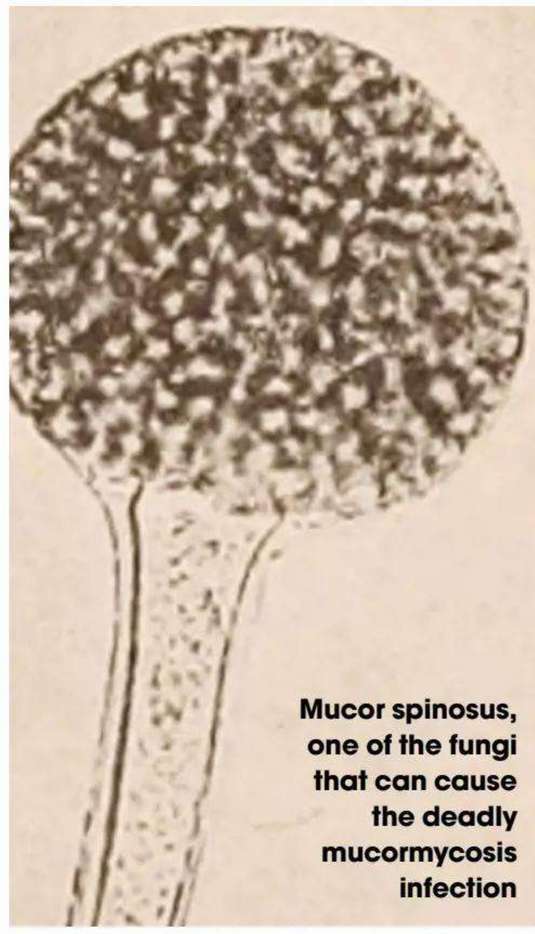
5 Great Kanto

A 7.9-magnitude earthquake on 1 September 1923 triggered a firestorm that burned up to 45 per cent of the city of Tokyo and killed over 140,000 people. This included 44,000 who were incinerated by a 100-metre (330-foot) fire tornado that ravaged the area.

© Alamy; Thinkstock; Peters & Zabransky

Surprising ways natural disasters can turn deadly

Forget rivers of lava and strong winds... Earth's most furious moments claim their victims in unexpected ways



Mucor spinosus, one of the fungi that can cause the deadly mucormycosis infection

Did you know? A tornado's damage path can be 80.5km (50mi) long.

Tornadoes

Airborne diseases

Tornadoes kill primarily with 'blunt force trauma' as flying objects hit people. But these flying objects can also carry infections. In 2011, a 1.1-kilometre (0.7-mile)-wide tornado blasted through Joplin, Missouri. It was an EF5 storm, with winds exceeding 319 kilometres per hour (198 miles per hour). It killed 158 people and injured nearly 1,000. Nearly a dozen people developed mucormycosis from soil penetrating their skin. This rare infection can be cured with harsh measures: strong antifungal drugs and the removal of damaged skin. At least three deaths linked to the tornado were caused by this.

Volcanoes

Global cooling

Following the Laki volcanic eruption of 1783, winter was so cold that as many as 8,000 more people than usual in the UK may have died as a result. The sulphur particles from the eruption had major effects on conditions in Europe, leading some to speculate that it even added to the poverty and famine that led to the French Revolution of 1789. Sometimes a volcano's cooling effects go global. The 1815 eruption of Mount Tambora – the largest in the past 10,000 years – not only killed 70,000 people, but contributed to a global cooling of about 0.5 degrees Celsius (32.9 degrees Fahrenheit) by injecting sulphur particles into the atmosphere.

Volcanoes

Toxic gases

In 1783, Iceland's Laki volcano erupted, spewing sulphurous compounds into the atmosphere for eight months. Few Icelanders died as a result of the lava flows themselves, but other effects of the eruption proved catastrophic. Acid rain drenched the crops, and huge amounts of hydrogen fluoride were released, which poisoned both the population and livestock. It's estimated 8,000 Icelanders died as a result. The sulphur dioxide from the eruption entered the jet stream and spread westward over Europe, through China and Russia, and then over America by way of Alaska and northern Canada. In Europe, thousands choked to death as they inhaled the poisonous cloud. It has been estimated that 23,000 people died in the British Isles alone. Scientists at the University of Leeds have estimated that a similar eruption today would kill around 142,000 people across Europe.

Swathes of land left barren

Liquefaction in Christchurch, New Zealand, after it was hit by an earthquake in 2011

Earthquakes

Liquefaction

When soil is saturated with water, it can turn to mush when an earthquake strikes, in a process known as liquefaction. This dramatically reduces the ability of soil to support the foundations of buildings, and accounted for much of the destruction in the harbour of Port-au-Prince during the 2010 earthquake in Haiti. Generally, but not always, liquefaction occurs near to the earthquake rupture, where the radiating seismic waves are strongest. However, the mud volcano island that formed off the southern coast of Pakistan in 2013 was hundreds of kilometres/miles away from the epicentre of the magnitude 7.7 earthquake that occurred on 24 September. Geologists believe a combination of liquefaction and methane from the pile of mud and sand that exists in the offshore region was responsible for the formation of the mud mound, which measured approximately 176 by 160 metres (577 by 525 feet).

Homes toppled by a landslide

Earthquakes

Landslides

The initial vibrations from an earthquake are the least of your worries if they're shaking an area with vulnerable geographical features. Particularly violent earthquakes can trigger secondary reactions – some of which prove far more deadly than the initial earthquake. The most infamous example of this phenomenon is tsunamis – huge water waves typically triggered by underwater earthquakes that can devastate coastal towns, such as the 2004 Indian Ocean tsunami, which claimed more than 230,000 lives across South Asia. But inland areas near mountains or hillsides aren't safe either. Seismic activity here can trigger chain reactions that cause massive landslides and avalanches, burying whole communities under rubble. In 2013, 100 people were killed in China's Gansu province when a magnitude 6.6 earthquake resulted in severe landslides.

© Getty / Alamy

Earth's extreme climates

From dry, polar deserts to wet, hot rainforests and everything in between, Earth has some amazing extreme climates

Mount Herschel in Antarctica, which has been affected by global warming

Climate goes far beyond weather. It explains why there are such predictably disparate regions on Earth and such wide variations in things like temperature, precipitation, humidity, wind, vegetation and plant life. There are a lot of different factors that play into the different climates present on our planet, and they work together in a complex way. One is the differences in how air circulates around the Earth. Depending on where you are located, you are in the path of a different wind belt or cell, with its own unique characteristics. They are considered the 'weathermakers' for the latitudes they occupy, as they both affect and are affected by temperatures on the Earth's surface.

Each of the five main lines of latitude – Arctic, Tropic of Cancer, the equator, Tropic of Capricorn and the Antarctic – also have a big impact on the climate. Most areas near the equator are hot, as the Sun is directly overhead with very little variation in temperature. As you move outwards on either side of the equator, into the tropics and then the middle latitudes, temperatures can vary widely in part because the Sun changes more drastically with the Earth's tilt and rotation. Once you reach the Poles, we're back to extremes, with temperatures consistently cold due to the distance from the Sun.

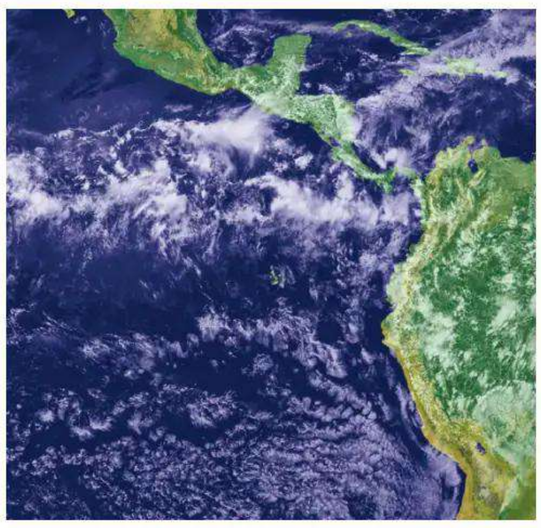
Topography also affects climate, and can supersede other factors. One striking example of this is California, which boasts several major different types of climate all in one state (some even have sub-climates). There is a Mediterranean climate along the coast and in some of the interior valleys. A desert climate is present in dry valleys and mountain ranges. Other areas of high elevation have more temperate climates and vary depending on proximity to the ocean. California even has areas of steppe, a type of grassland. High temperatures across the state can reach 38 degrees Celsius (100 degrees Fahrenheit) and lows can get down to -11 degrees Celsius (12 degrees Fahrenheit). Thanks to its coast and the Andes, Chile can also boast a number of different climates within its borders. Both California and Chile have numerous examples of micro-climates – areas where the climate can vary widely within just a few square kilometres/miles, thanks to differences in topography.

The Earth has undergone extreme climate shifts in its history, one such being the ice ages. Ice ages are periods when the temperature of the planet as a whole has gone down enough to create more alpine ice and polar ice sheets. In the Seventies many scientists speculated

© Andrew Mandemaker 2006

Atmospheric circulation

Atmospheric circulation is the way that the Sun's energy is dispersed across the Earth's surface. This large-scale air movement behaves in predictable patterns and follows specific cycles, creating different climates across the globe.



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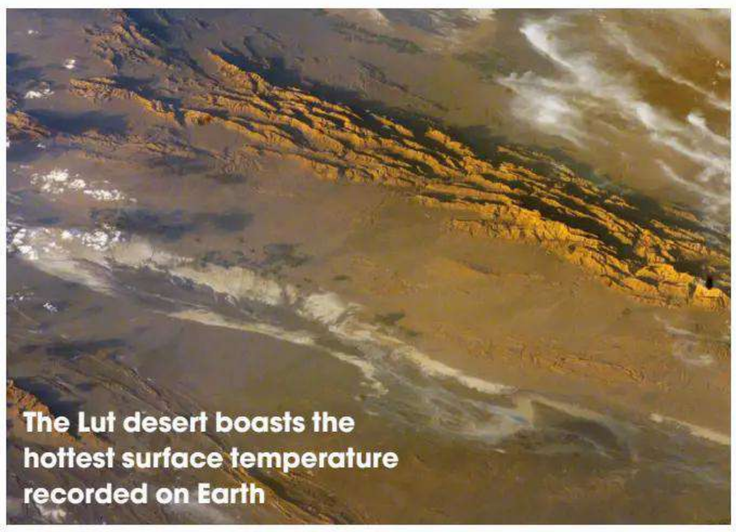
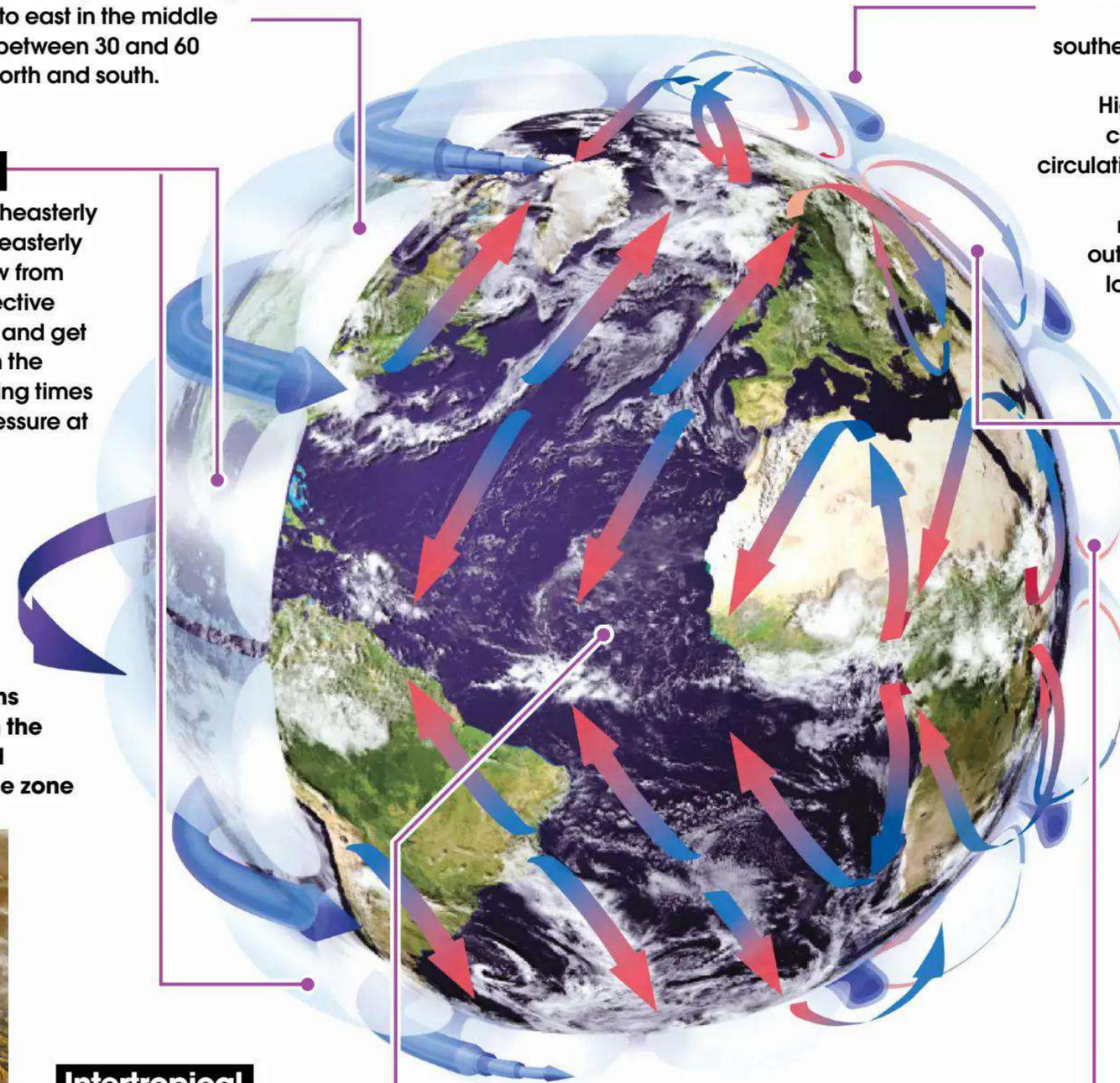
The Doldrums are found in the intertropical convergence zone



© NASA

The Lut desert boasts the hottest surface temperature recorded on Earth



Westerlies

These winds blow predominantly from west to east in the middle latitudes, between 30 and 60 degrees north and south.

Trades

These northeasterly and southeasterly winds blow from their respective directions and get stronger in the winter during times of high pressure at the Poles.

Intertropical convergence zone

This area in between the various types of prevailing winds is very calm, with little to no wind.

Polar cell

The Polar cells are the northern and southernmost wind belts circling the Earth. High-pressure areas come from cold air circulating over the Poles, which heats and rises as they move outwards and create low-pressure areas.

Ferrel cell

Unlike the other cells, the Ferrel cell is not a closed loop. It is known as the 'zone of mixing', where the air from the Polar cells and Hadley cells converge.

Hadley cell

When warm, humid air rises near the equator, it travels towards the Poles and descends into a low-pressure area.

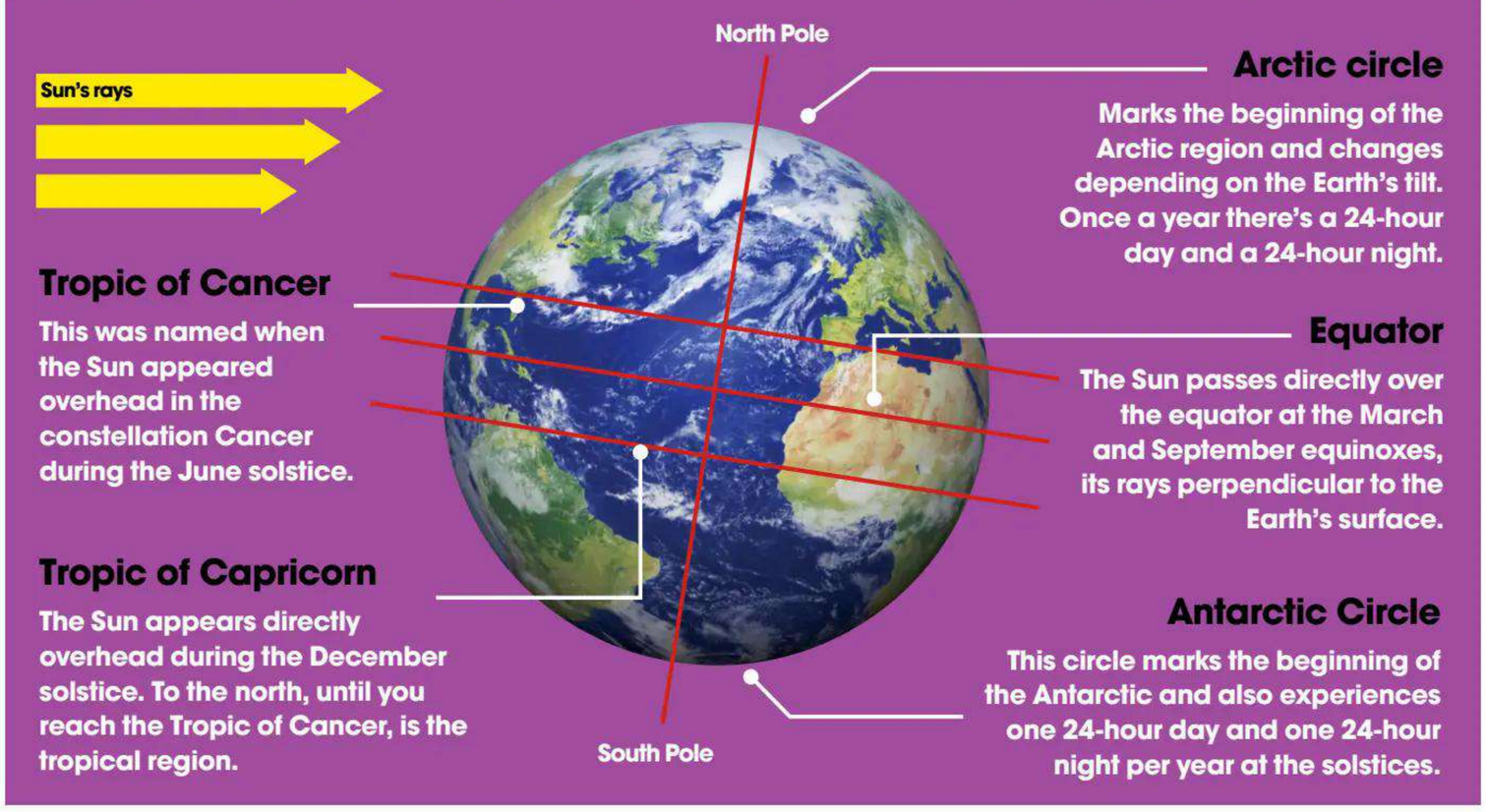
© DK Images

that we could be headed for another ice age. However, today the prevailing theory is that the Earth will experience a climate change due to global warming. While believers in the next ice age did not specify human involvement, global warming theorists point to an increase in greenhouse gases as a cause for rising temperatures around the globe. These gases absorb and emit radiation, and are a result of an increase in carbon dioxide in the Earth's atmosphere due to burning fossil fuels.

Another possible cause for climate change is deforestation, which has affected climates in areas such as rainforests. There is a general consensus among the scientific community that the Earth's surface temperatures increased by 0.74 degrees Celsius (1.33 degrees Fahrenheit) during the last century. However, the possibility of climate change to the Earth as a whole, remains controversial among the public.

Changes in latitudes, Changes in attitudes

Latitude – whether you're north or south of the equator – has a huge impact on a region's climate. At the equator and the poles are the most extreme temperatures: very hot due to a lot of incident sunlight, or very cold due to a low amount of sunlight. The 'in between' areas, or 'middle' latitudes, generally have definitive seasons and wider ranges in temperature.



Arctic circle

Marks the beginning of the Arctic region and changes depending on the Earth's tilt. Once a year there's a 24-hour day and a 24-hour night.

Tropic of Cancer

This was named when the Sun appeared overhead in the constellation Cancer during the June solstice.

Equator

The Sun passes directly over the equator at the March and September equinoxes, its rays perpendicular to the Earth's surface.

Tropic of Capricorn

The Sun appears directly overhead during the December solstice. To the north, until you reach the Tropic of Cancer, is the tropical region.

Antarctic Circle

This circle marks the beginning of the Antarctic and also experiences one 24-hour day and one 24-hour night per year at the solstices.

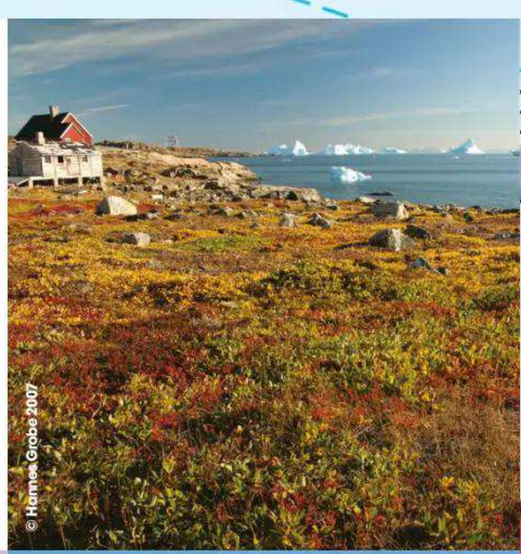
Climate zones

The Earth's climates can be classified into different zones that have similar conditions, vegetation, types of seasons and temperatures

Polar/tundra

Generally the tundra has one month with an average temperature of 0°C (32°F), but no months with an average high greater than 10°C (50°F). There is low rainfall and snowfall, and vegetation comprises dwarf shrubs, lichen and grasses.

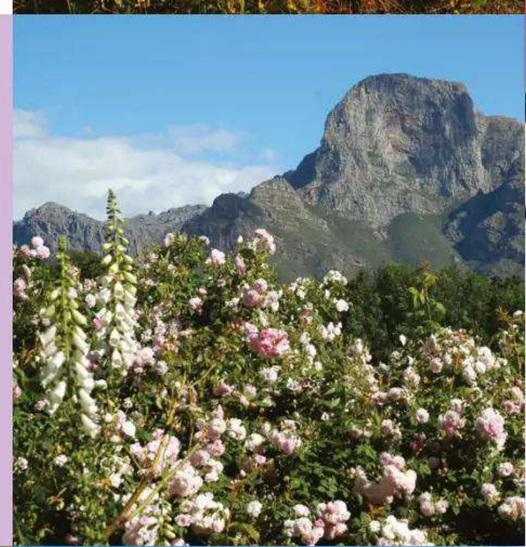
Examples: Alaska, northern Canada and Russia, Greenland, Iceland and northern Scandinavia.



Boreal/coniferous forest

Boreal/coniferous forests are usually in areas of higher elevation, between 900 metres (2,953 feet) and 1,300 metres (4,265 feet) above sea level. There is a high level of both rain and snowfall and very cold temperatures.

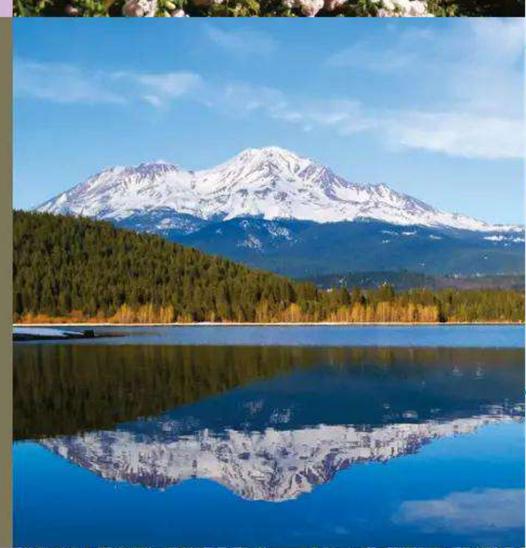
Examples: Uplands of New England, inland Canada and Alaska, northern Norway, much of northern Asia.



Mountain

Mountain regions are above the tree line – the line at which trees stop growing due to extreme cold or dryness. High elevations mean colder temperatures because air expands when it rises. There are strong winds and there is usually a lot of snowfall.

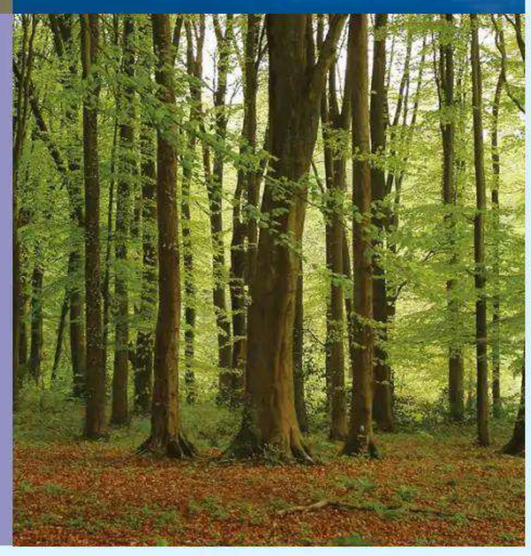
Examples: Rocky Mountains, Himalayas, Alps, Pyrenees, Andes.



Temperate/ deciduous forest

As its name implies, this climate is very moderate, with distinct seasons. Summer highs can reach 32°C (90°F) and winter lows can reach -1°C (30°F). Rainfall and snowfall can vary widely.

Examples: Eastern and western United States, Canada, Europe, West Asia.



COLD! Snag, Yukon, Canada
Lowest recorded temperature of -63° C (-81°F).

WET! Mount Waialeale, HI, USA
Average annual rainfall of 11m (36ft).

COLD! North Ice, Greenland
Lowest recorded temperature of -66°C (-87°F).

CALM! Oak Ridge, TN, USA
Average annual wind speed of 7kph (4mph).

WINDY! Chicago, IL, USA
Known as the Windy City but not even the windiest in the US.

WINDY! Mount Washington, USA
Holds the North American & Western Hemisphere Record for highest recorded wind speed.

CALM! Walla Walla, WA, USA
Average annual wind speed 9kph (5.1mph).

HOT! Death Valley, Arizona, USA
Highest recorded temperature of 57°C (134°F).

CALM! Talkeetna, AK, USA
Average annual wind speed of 8kph (5mph).

WET! Debundscha, Cameroon
Average annual rainfall of 10m (34ft).

DRY! Batagues, Mexico
Average annual rainfall of 3cm (1.2in).

WET! Quibdo, Columbia
Average annual rainfall of 8.9m (29.5ft).

STILLEST

Rising air
The Doldrums

Sailors travelling through this region near the equator, known as the intertropical convergence zone (ITCZ), called it 'The Doldrums' because the air is so still. Rather than blowing as wind, air rises due to convection as it is heated by the Sun. This is generally located about five degrees north and south of the equator, but can move as much as 45 degrees in either direction. The ITCZ is where the northeast and southeast trade winds converge, creating an area of low pressure.

DRIEST

Dry by the sea
Arica, Chile

The Atacama desert is the driest region on Earth, and Arica is the driest city. There are regions that have not received rainfall in tens of millions of years. Arica itself receives about 0.75 millimetres (0.03 inches) per year, and once went a span of 173 months without rainfall. Despite this, Arica's average annual high is only around 27°C (80°F).

WINDIEST

A special kind of wind
Commonwealth Bay, Antarctica

With an annual mean wind speed of over 80kph (50 mph) and winds regularly topping 240kph (149 mph), this is the windiest place on Earth. Katabatic wind also occurs, where cold air rushes down a steep, ice shield from the rocky point of Cape Denison towards the water.

HOTTEST

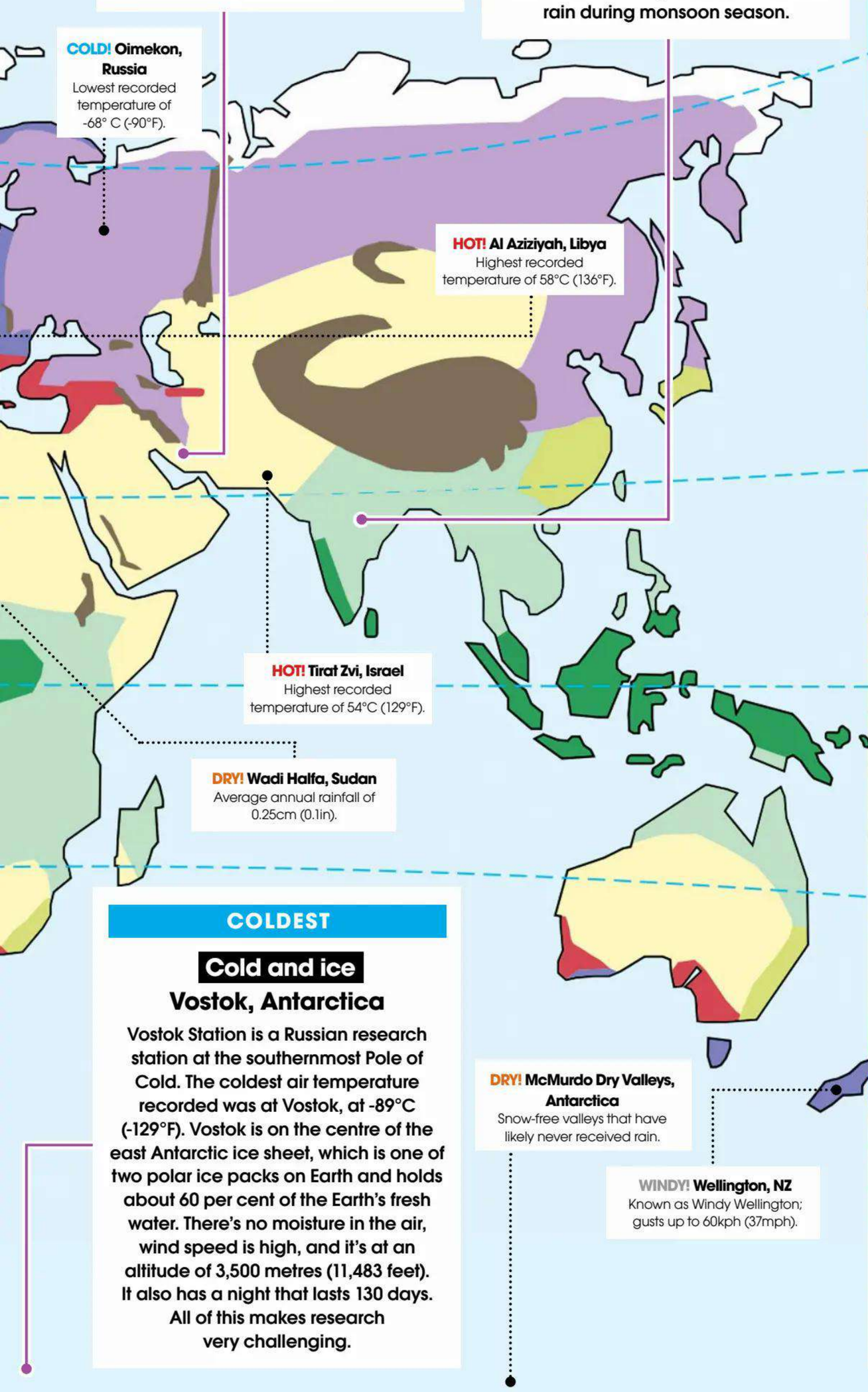
Toasted wheat
Lut desert, Iran

This large desert basin comprises mostly salt, sand and rock. Its title as the hottest place on Earth is in dispute, but according to NASA satellite measurements in 2005 the average land temperature is 71°C (159°F). Surrounded by mountains, it is considered a dry drainage basin. One area is known as Gandom Beriyan, Persian for 'toasted wheat', due to a story that spilled wheat scorched in just a few days.

WETTEST

Water, water!
Mawsynram, India

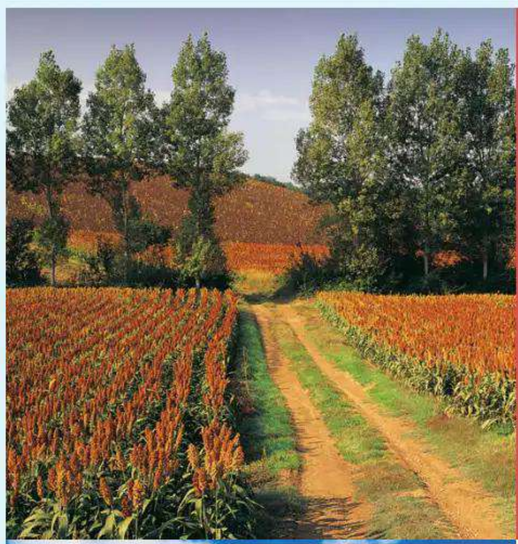
The wettest place actually varies between Mawsynram and the nearby city of Cherrapunji, with a difference of less than 1,000 milimetres (39 inches) of annual rainfall. Mawsynram in northeast India has an average annual rainfall of nearly 12 metres (39 feet). Mawsynram is in the Khsai Hills and about 1,400 metres (4,593 feet) above sea level. Air blowing in from nearby plains cools as it rises, trapping moisture in clouds, which release their rain during monsoon season.



COLDEST

Cold and ice
Vostok, Antarctica

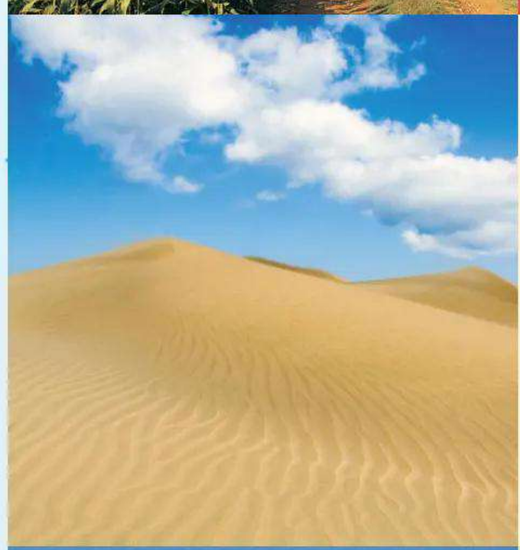
Vostok Station is a Russian research station at the southernmost Pole of Cold. The coldest air temperature recorded was at Vostok, at -89°C (-129°F). Vostok is on the centre of the east Antarctic ice sheet, which is one of two polar ice packs on Earth and holds about 60 per cent of the Earth's fresh water. There's no moisture in the air, wind speed is high, and it's at an altitude of 3,500 metres (11,483 feet). It also has a night that lasts 130 days. All of this makes research very challenging.



Mediterranean

Although it is generally centred around the Mediterranean basin, this climate exists in other parts of the world that are near warm bodies of water. There are cool, wet winters and hot, dry summers due to subtropic air pressures.

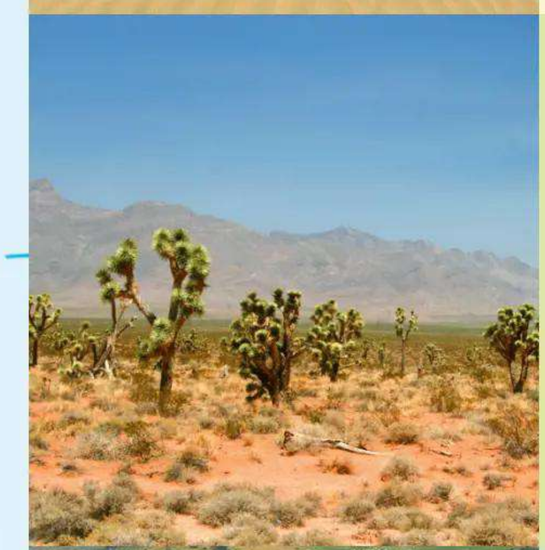
Examples: Mediterranean, California, western and south Australia, parts of central Asia.



Desert

The main defining characteristic of deserts is the lack of precipitation – most get less than 250mm (10in) per year. Many are so dry that there is a moisture deficit and very little vegetation. Deserts are thought of as hot and sandy, but there are polar deserts as well.

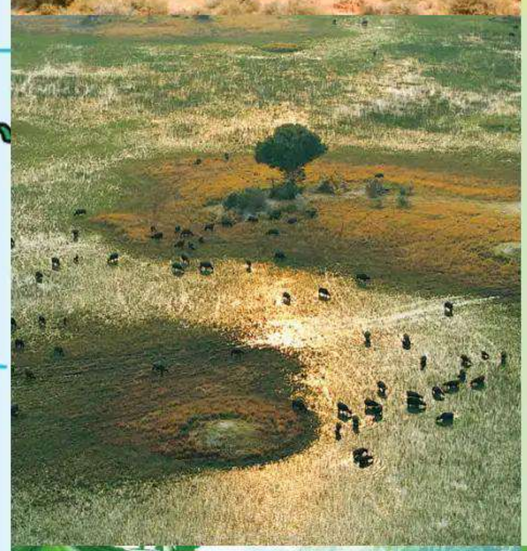
Examples: Arabian, Sahara, Gobi, Kalahari, Antarctic, Arctic.



Temperate grassland

These areas have no large trees, just grasses and shrubs. There are wide variations in temperature. Winter lows can reach -40°C (-40°F) and summer highs can go up to 38°C (100°F). Rainfall averages 50cm (20in) per year.

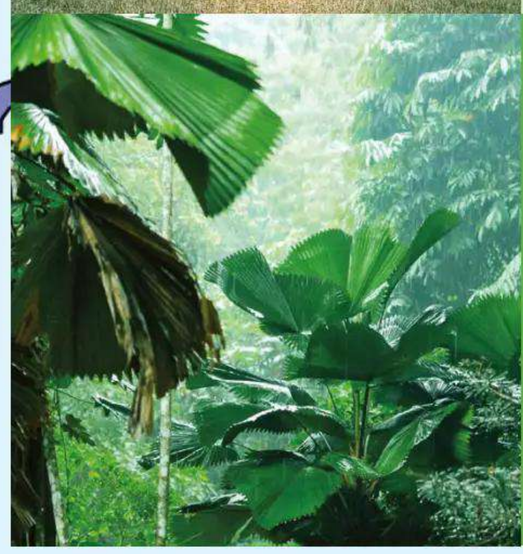
Examples: Prairies of North America, steppes of Europe, pampas of South America.



Tropical grassland/savannah

Savannahs have grassy areas with widely spaced tree cover. There is generally just one rainy season that can produce up to 150cm (59in) of precipitation over the space of as little as a few weeks. Average temperature is 30°C (86°F).

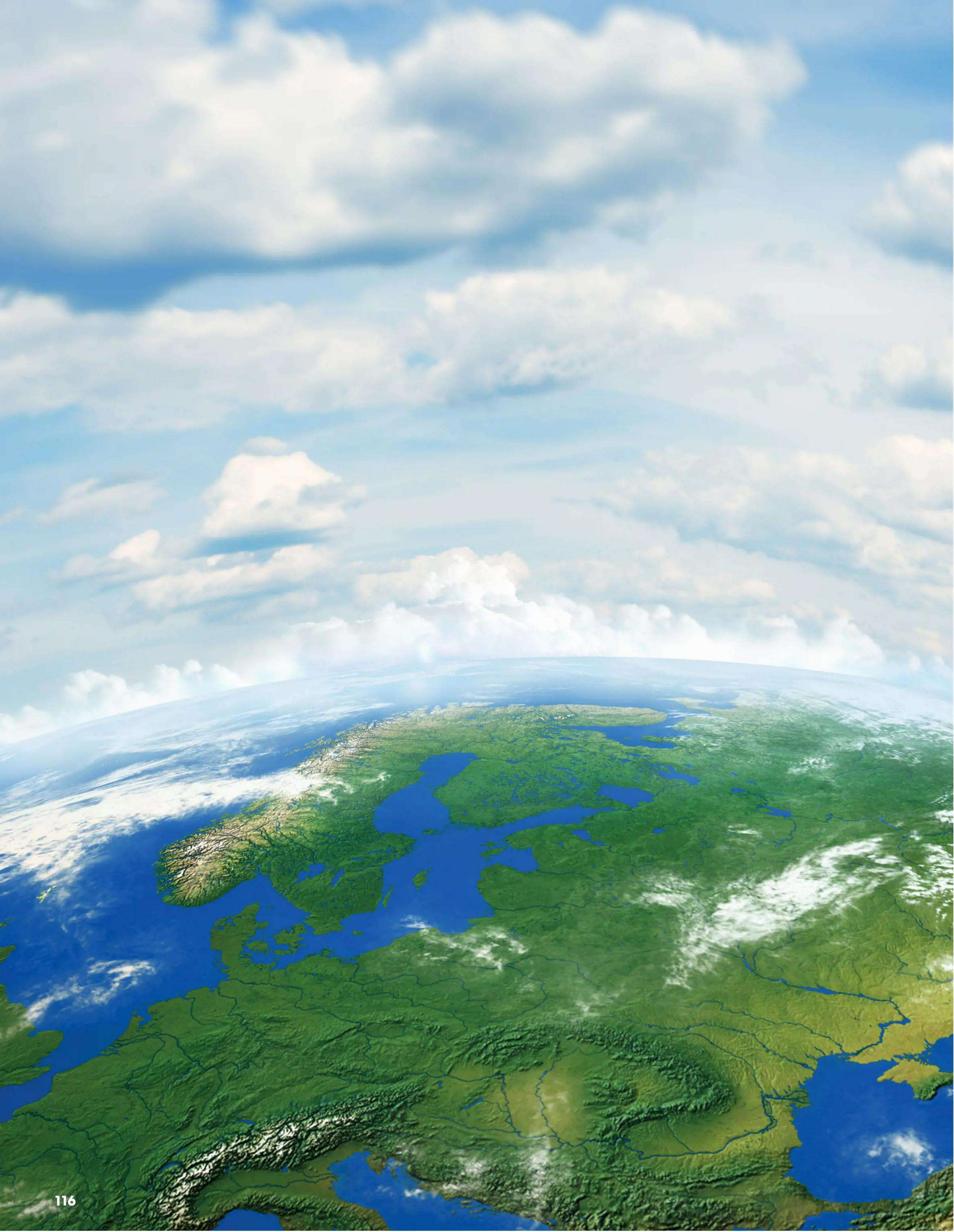
Examples: African savanna, northern Australia, southern United States.



Tropical rainforest

Tropical rainforests are found within 28 degrees north or south of the Equator. Annual rainfall is about 200cm (80in) and the average temperature is always above 20°C (68°F) no matter what time of year. There is a dense tree canopy and little undergrowth.

Examples: Africa, Asia, Australia, Central America, South America.



Climate change

How our climate is changing

Here are eight signs of the human impact on Earth's climate and environment

Did you know?
Since 1970, the global surface temperature has risen faster than in any other 50-year period over the past 2,000 years.

Climate change is described as a large-scale and long-term shift in Earth's climatic patterns and average temperatures. These shifts have been exacerbated by human activity. For example, greenhouse gas emissions of carbon dioxide (CO_2) reached record highs of 419.3 parts per million in 2023. CO_2 naturally soaks up infrared radiation from the Sun and distributes the heat it produces across Earth, acting like a big blanket. This results in the rise of global temperatures, causing widespread alterations in Earth's climate. According to a 2023 NOAA report, Earth's combined land and ocean temperature has increased by an average rate of 0.08 degrees Celsius (0.14 degrees Fahrenheit) each decade since 1880.

As a result, countless aspects of our environment and ecosystems are altering. From record-breaking forest fires to unprecedented shifts in weather, there are many warning signs from all corners of our planet that show our world is changing.

Animal migration

1 Seasonal cues play a role in informing animals when it's time to migrate, when to find a partner to mate with and when and where they can find food. The migration and reproduction timelines of several Arctic animals have changed over the years in response to the effects of climate change. Researchers discovered that eagles in the Arctic had been migrating half a day earlier each year between 1991 and 2019, which led to a migration timing that starts two weeks earlier. Similarly, Arctic caribou populations have adapted to the changing seasons and are having their offspring earlier to coincide with their changing environment.

Caribou crossing the Arctic National Wildlife Refuge in Alaska

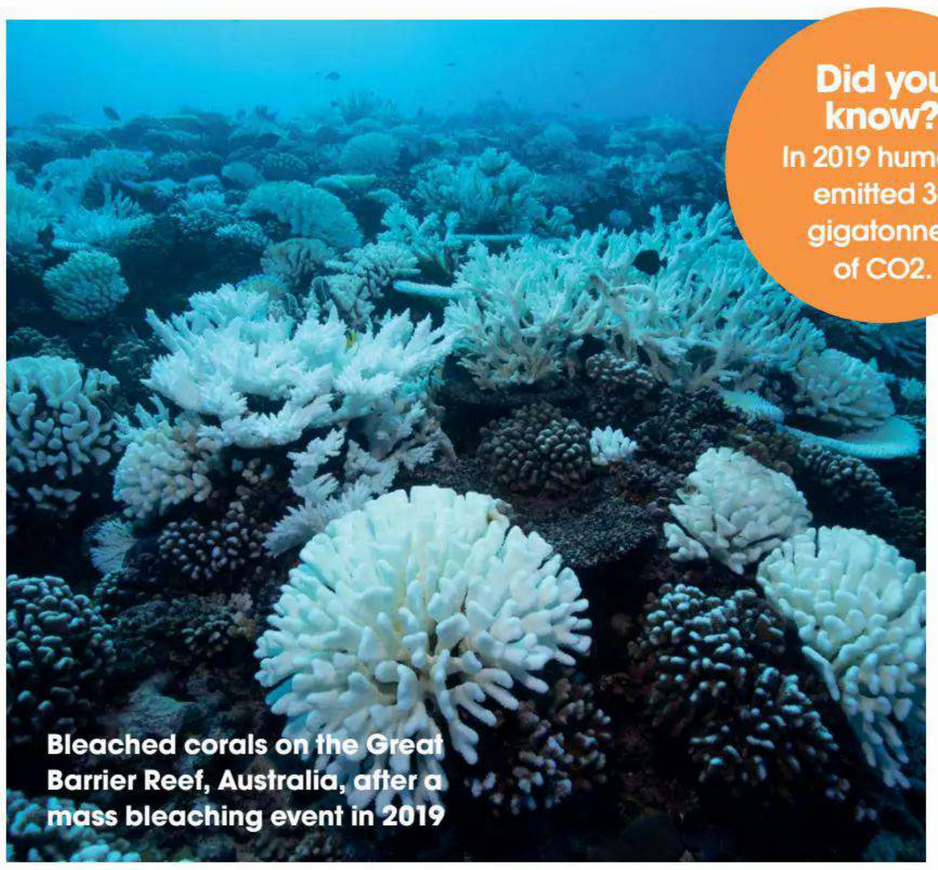
Large algal blooms on Lake Balaton, Hungary, taken 31 August 2019

Algal blooms

2 As waters warm around the world and global emissions of CO_2 increase, harmful algae can thrive. Large algal blooms tend to appear on lakes and shorelines during the summer, but these blooms are getting bigger. Researchers at the Carnegie Institution for Science conducted a study in 2019 and found that summertime algal blooms increased in more than two-thirds of the 71 sampled lakes, which spanned 33 countries across six continents, since the late 1980s. These blooms can be deadly: they form dead zones that starve marine life of oxygen and light, and some even release lethal toxins. In 2020, a 22.5-kilometre (14-mile) toxic algal bloom called the 'red tide' drifted along the Florida coastline, killing more than 100 manatees and 127 dolphins.

Coral bleaching

3 Between a quarter and a third of all marine species rely on coral reefs to survive at some point in their lives, but extreme bleaching events are destroying them. As global temperatures increase, bleach events are becoming more frequent. A rise in temperature, along with increased levels of carbon dioxide, strip away the mutualistic algae that are vital to the coral's survival, leaving the coral bleached white and dead. In 2016 and 2017, 50 per cent of corals in the Great Barrier Reef were killed. Coral reefs in all 29 reef-containing World Heritage Sites could be lost by the end of the century if current global CO_2 emissions aren't reduced.



Bleached corals on the Great Barrier Reef, Australia, after a mass bleaching event in 2019

Did you know?
In 2019 humans emitted 36 gigatonnes of CO_2.

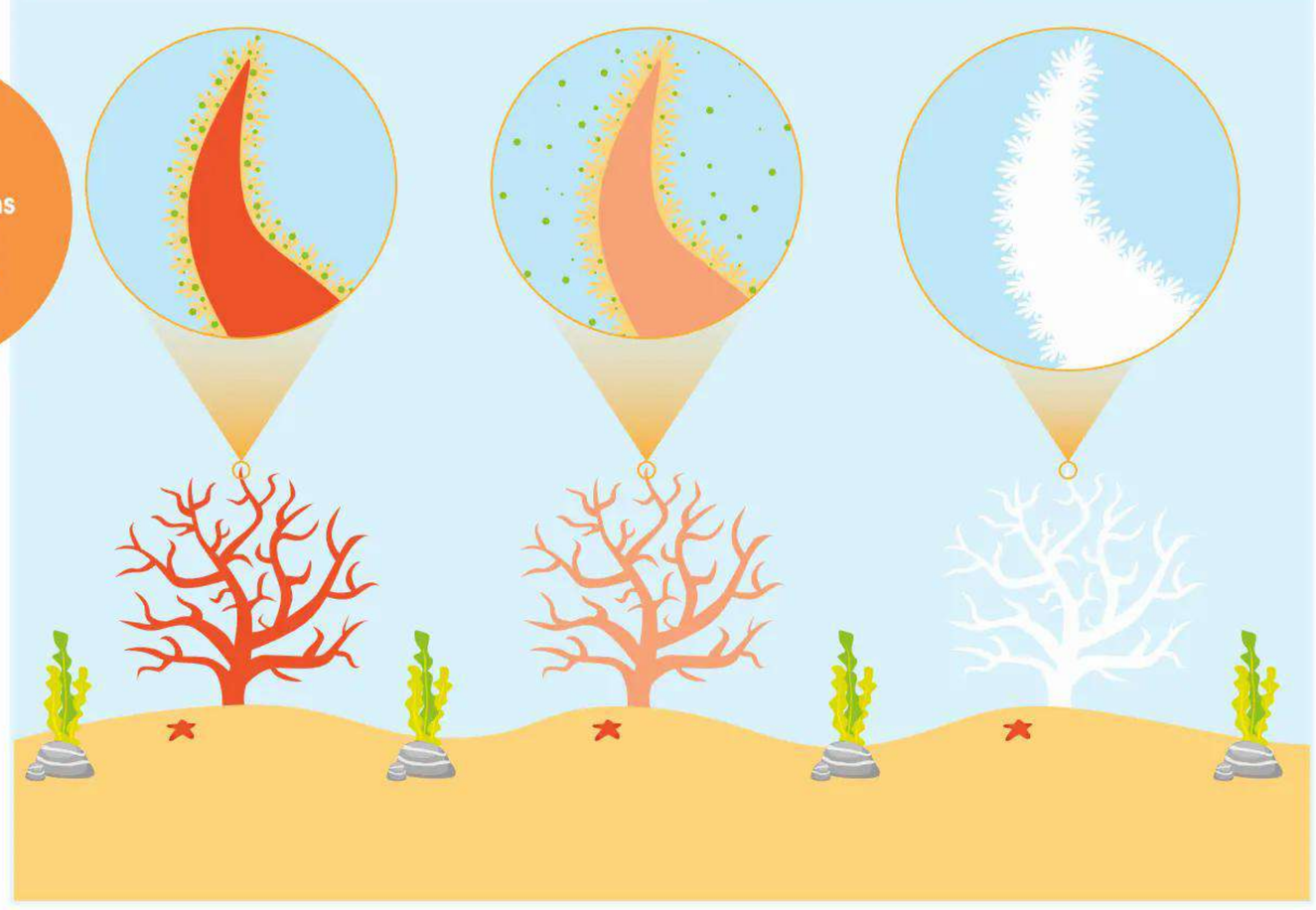
How coral becomes bleached

A breakdown in a symbiotic relationship leads to the demise of coral

Healthy coral
Zooxanthellae algae live within the tissue of corals for protection, and in return the algae provide corals with oxygen and nutrients.

Stressed coral
When temperatures increase, pollution levels rise and waters become more acidic. Algae begin to evacuate, reducing the amount of nutrients corals receive.

Bleached coral
Once all the algae has vacated, corals lose their food source. Algae also give corals their vibrant colours – without them, they turn ghostly white.



© Getty / Lauren Dauphin, using Landsat data from the U.S. Geological Survey

Heavy rain flooding the Nine Elms district of London, 25 July 2021

Flooding

4 Extreme flooding occurs where urbanisation has changed the landscape of floodplains or low-lying coastal regions. A rise in global temperatures increases the likelihood of extreme weather, which leads to flooding. As the atmosphere warms, it holds more moisture, meaning heavier precipitation. For around every one degree Celsius (1.8 degrees Fahrenheit) increase, the atmosphere holds around seven per cent more water vapour. Studies show that the number of extreme precipitation events in the US could increase to two to three times its historical average by the end of the century.

A coastal cliff fall on Dorset's Jurassic Coast, England

Did you know?
2023 was the second-hottest year on record, with 2024 the hottest.

Melting the ice

5 Around ten per cent of Earth's land is covered in ice, and almost 90 per cent of that is in Antarctica. Greenhouse gas emissions and a rising global temperature have caused these vital ice stores to melt. Before the year 2100, it's estimated between a third and half of the world's remaining glaciers will have melted. Since the 1990s, Greenland and Antarctica have lost around 6.6 trillion tonnes of ice. The rate of ice loss is also increasing; researchers found that between 1994 and 2017, the rate of ice loss accelerated by 57 per cent, from around 800 billion tonnes to around 1.2 trillion tonnes a year.

Melting ice has a knock-on effect of increasing sea levels

Coastal erosion

6 Coastal erosion occurs when the water of the ocean beats against coastal rocks and reduces them to rubble, eventually grinding them into sand. As sea levels rise around the world – a knock-on effect of melting ice caps – the water can extend further up coastal regions, increasing the rate of erosion. Erosion at the coastline can occur in several ways: simple abrasion from waves can grind rock and stone away, but it can also dredge up rock and stone from the seabed and throw them against the cliffs, chipping away at the coastline. Hydraulic action also occurs when air trapped between the rocks of a cliff compresses under the force of the wave, weakening structural integrity. Britain has some of the fastest-eroding coastlines in Europe and loses around four metres (13 feet) of coastline each year in heavily affected areas.

Landlocked lake dry-out

7 Endorheic lakes are landlocked and don't drain into other bodies of water. Water levels are determined by precipitation and the rate of evaporation, making them a useful indicator of climate change and rising global temperatures. Between 2002 and 2016, approximately 106.3 gigatonnes of water was lost from the endorheic system worldwide. This can put pressure on local communities that rely on the lakes, as well as displacing water into other water systems, which could cause flooding.

The lakebed of Suesca Lagoon, Colombia, is dried out and thirsty for rain

Antarctica's ice melt

How the South Pole has changed over the last few decades

Antarctica is a large continent of ice that experiences fluctuations in the amount of sea ice that surrounds it. During the winter months this ice expands, retreating during the summer as the weather gets warmer. Since the beginning of satellite observations of the icy continent in 1979, Antarctic sea ice has increased by one per cent per decade. However, since 2014 Antarctica has experienced several drops in sea ice production. In 2017 Antarctica had a record-breaking low annual sea ice coverage of 2.1 million square kilometres (815,000 square miles) – 184,000 square kilometres (71,000 square miles) below the previous minimum. The images on the opposite page show how this ice coverage has changed over the decades, during the Antarctic summer retreat.

Wildfires

8 Rising global temperatures cause increased evaporation and the drying out of forests, along with the soil they stand on, making them more flammable. Around 90 per cent of wildfires are ignited by humans; the rest are caused by natural means, such as lightning and even volcanic activity. Fire only needs three things to blaze: fuel, oxygen and heat. When wood is heated to the point it burns – known as its flash point – it releases hydrocarbon gas that combines with the oxygen in the air and combusts to produce fire. As climate change continues to turn forests into kindling, these fires have increased in size – California lost a record-breaking 17.2 billion square metres (4,257,863 acres) of forest in 2020.

How wildfires spread

Once one gets going, it takes a lot of work to stop it

1 Ignition
Trees ignite when they reach their flash point (around 300 degrees Celsius/572 degrees Fahrenheit).

2 Travel
Several factors contribute to the way a wildfire spreads, such as winds carrying hot embers, the topography of forests and the weather.

3 Fire damage
Radiant heat, embers and smoke are the main causes of damage to urban areas affected by wildfires.

4 Crossing barriers
Embers are able to cross over natural barriers, such as rivers and roads, on the wind. This allows the fire to spread even greater distances.

5 Town fires
Buildings can perpetuate the spread of a wildfire if they are positioned close together. This allows flames to hop from one building to another.

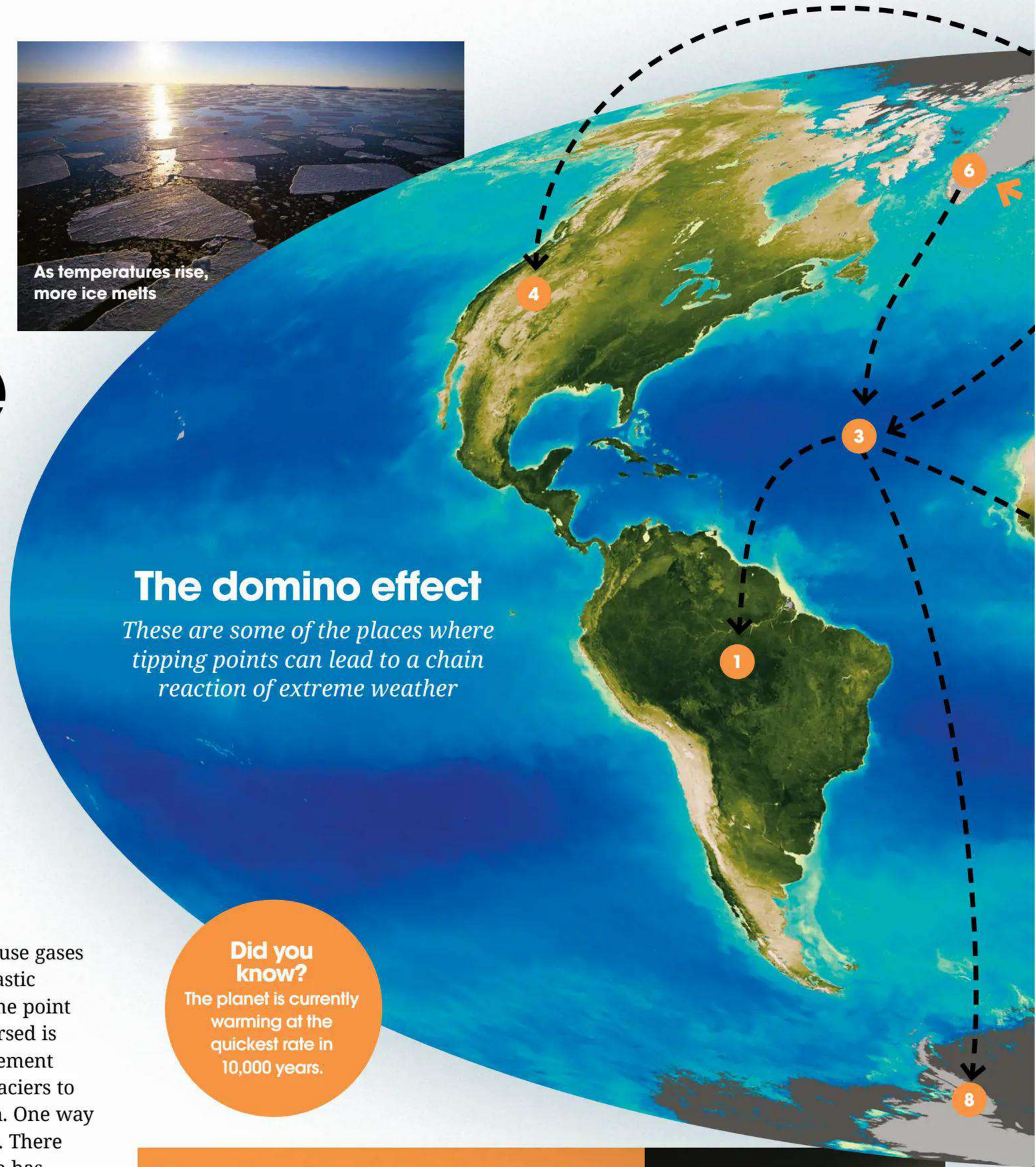
6 Smoke
The smoke emitted from a wildfire is largely made up of water vapour. However, it also contains several harmful compounds such as carbon dioxide and monoxide, nitrogen oxide and fine toxic particles.

Did you know?
Arctic sea ice is reducing by 13 per cent per decade.

What is the climate tipping point?

Discover what might happen now that we've reached this critical threshold

As temperatures rise, more ice melts



The domino effect

These are some of the places where tipping points can lead to a chain reaction of extreme weather

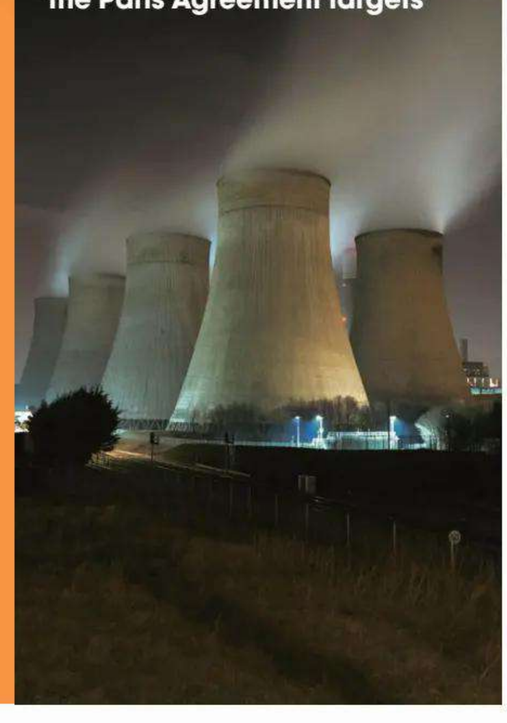
Did you know?
The planet is currently warming at the quickest rate in 10,000 years.

There's a limit to how much greenhouse gases our planet can absorb without a drastic change to the climate worldwide. The point at which this can no longer be reversed is called the tipping point. For each element of climate change – from melting glaciers to declining coral reefs – there is a point of no return. One way to envisage this is to think about a child on a slide. There is a crucial point in this journey in which someone has committed to going down the slide, and they can't go back up. This transforms their state from being at the top to being at the bottom.

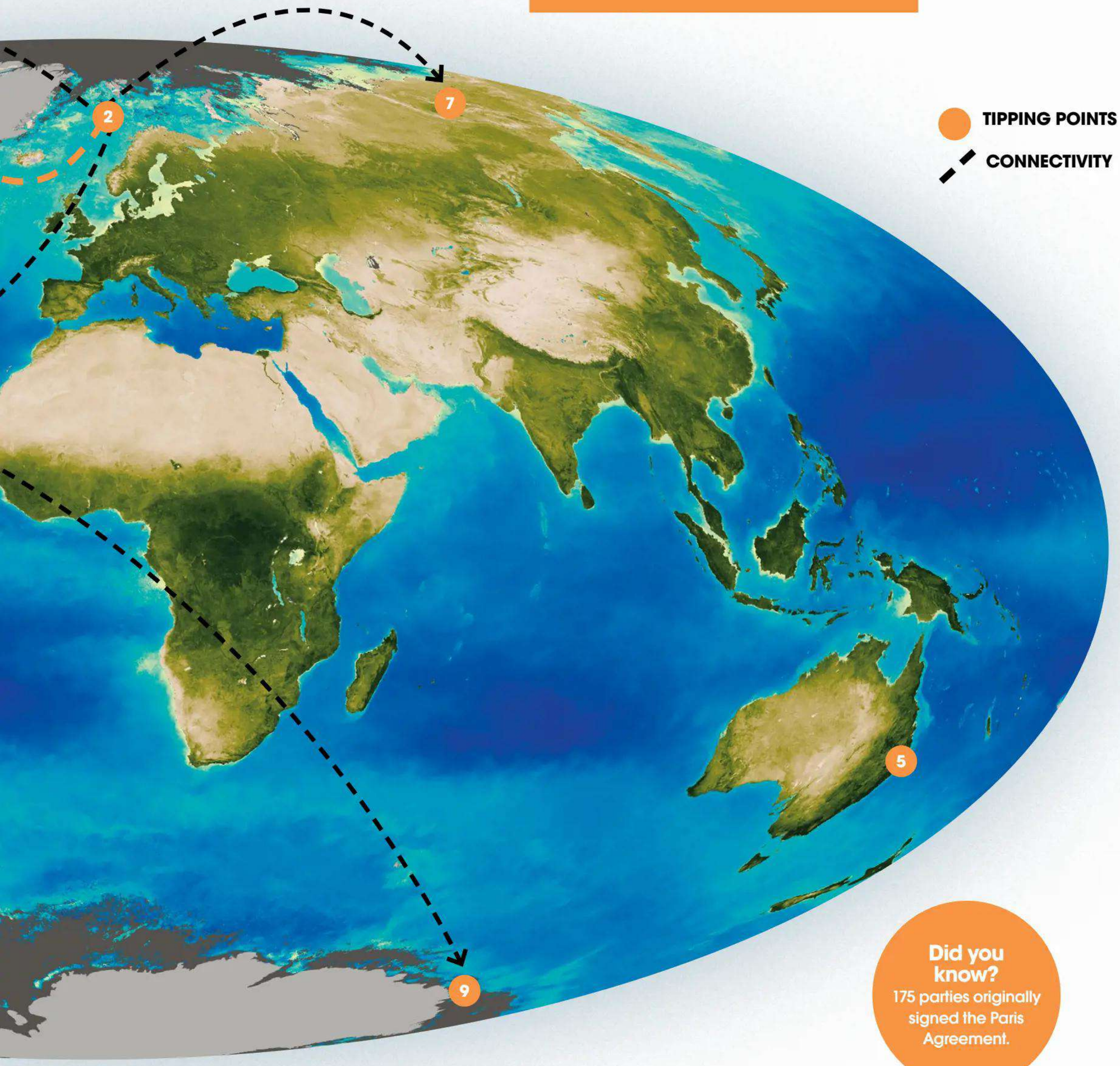
It's important to learn about and act on the impact of global warming on the planet before it becomes irreversible, but when will this be? In the early 2000s, scientists estimated that when human activity increased the global temperature by four degrees Celsius (7.2 degrees Fahrenheit), the climate system would reach its tipping point and undergo radical changes. In 2015, this increase was revised, with scientists estimating that the planet could reach its critical threshold after a rise of just 1.5 degrees Celsius (2.7 degrees Fahrenheit). Unfortunately, we exceeded this threshold in July 2023 and in July 2024 a new record was set for the highest daily global average temperature at 17.16 degrees Celsius (62.88 degrees Fahrenheit). According to the UN Secretary General global emissions need to fall by nine per cent every year until 2030 to avoid permanently breaching the tipping point before it is too late.

The Paris Agreement

This international treaty came into effect in November 2016 and aims to reduce the global temperature rise. It's the world's first internationally binding agreement, which means that governments all over the world have agreed to make contributions towards limiting their country's greenhouse gas emissions. This agreement has 195 parties and requires each to submit their plans to support the environment, as well as being transparent about their impact on the planet by relaying data of their produced emissions. Since the world's focus on pulling back from the climate tipping point, more than 130 countries now aim to reduce their greenhouse gas emissions to net zero by 2050. Eight have declared that they've already met this target. This is achieved by introducing renewable energy systems and absorbing existing carbon dioxide from the atmosphere.



Sixty per cent of oil and 90 per cent of coal needs to remain unextracted by 2050 to meet the Paris Agreement targets



Did you know?
175 parties originally signed the Paris Agreement.

1 Amazon rainforest
Climate change causes droughts in the Amazon. The reduced Atlantic circulation carries less precipitation to the area.

2 Arctic sea ice
Warmer global temperatures increase the melting rate of Arctic ice. This reduces the ocean's temperature contrast, weakening currents. It also weakens jet streams, which can lead to global wildfires.

3 Atlantic circulation
As the ocean's circulation is reduced, the northern Atlantic experiences cooling as less heat reaches it, while the southern Atlantic experiences warming.

4 Boreal forest
Warmer conditions cause more frequent wildfires here. It also increases the prevalence of invasive pests such as Siberian moths or mountain pine beetles. These can wipe out some species of trees.

5 Coral reef reduction
Fluctuations in water temperature cause coral to lose the algae that covers it in a process called coral bleaching.

6 Fluctuations in water
Carbon stored in the ice sheet is released when it melts. It has released 500 gigatonnes of carbon so far and is halfway towards the tipping point for the southern portion of the sheet.

7 Permafrost
As Arctic temperatures are increasing, frozen land thaws and breaks apart. This releases greenhouse gases that are stored in the permafrost.

8 West Antarctic ice sheet
The reduction in this ice sheet is considered a tipping point as now that temperatures have risen to 1.5 degrees above pre-industrial levels, it is expected to suffer from irreversible melting, increasing global sea levels.

9 Wilkes Basin
This area of East Antarctica will reach its tipping point at a temperature increase of three degrees.

5 Facts Critical climate indicators

1 Rising global temperatures
Now that global temperatures have reached 1.5 degrees Celsius (2.7 degrees Fahrenheit) higher than pre-industrial levels the unnatural warming is estimated to trigger other climate tipping points.

2 Melting ice caps
The mass reduction in sea ice caused by global warming impacts the temperature of the oceans as sunlight is no longer reflected off the ice. Water below this ice is denser and sinks to cause ocean circulation. This reduces as the ice melts.

3 Extreme weather events
Life-threatening weather events such as intense heat waves, wildfires, hurricanes, storms, droughts and floods become more common as greenhouse gases build up in the atmosphere.

4 Greenhouse gas concentration
The more carbon dioxide and other greenhouse gases are released by burning fossil fuels, the more of the Sun's heat is trapped in the atmosphere by the thick blanket of gas.

5 Ocean acidification
The ocean absorbs a third of carbon dioxide produced by human activity. This makes the waters more acidic and hostile to sea life.

© Getty

Can we control the weather?

How existing and future technologies could help humans manipulate the climate

CLIMATE CHANGE

It may be the topic of daily small talk, but the weather and its shifting states has a big impact on the planet as a whole. In some countries, a prolonged lack of rain creates harsh, dry conditions, while others are constantly threatened by surges of floodwater. Severe weather varies drastically from country to country, but on the whole, global average temperatures are steadily increasing.

As modern technology advances and our understanding of meteorological processes grows, scientists are discovering new ways to control the weather. Instead of succumbing to nature's schedule, projects are in place to make the skies rain, remove carbon dioxide (CO2) from the atmosphere and prevent extreme weather events such as hurricanes and flooding.

Our reasons for controlling the weather can vary from the convenient to the essential. Geoengineering is the term used to describe the manipulation of weather to combat the effects of global warming. These methods are generally split into two categories: carbon dioxide removal and solar geoengineering. The intention of geoengineering is to protect the planet. However, some scientists believe we shouldn't play with nature. The outcome may appear positive when analysed in theory, but what about any consequences that we're unaware of? Humans have played a significant role in altering Earth's climate over the decades, and many believe that to control the weather for the better, we should focus on reversing our actions. This includes using less fossil fuels and preserving plant life.

Did you know?
Cloud seeding enhances rainfall by up to 35 per cent.

Not all weather-controlling technology is developed for the good of the planet – sometimes it's to tackle issues on a smaller scale. For example, China has been known to use its weather-modification program to control weather forecasts for events such as the Olympics. Before the Beijing Olympics in 2008, the country carried out cloud seeding to create rain in the clouds above the capital, ensuring that the rain fell before events like the opening ceremony, rather than during them.

Cloud combat

During the Vietnam War, the US army used cloud seeding to alter the weather. The aim was to prolong the monsoon season in Vietnam, making fighting more difficult for the enemy. The plan was named 'Operation Popeye' and meant that US troops were more prepared for the extended rainy season. Operation Popeye used rain as a weapon to destroy roads and flood rivers. To achieve this, military pilots flew over selected regions with canisters of silver or lead iodide. The canisters were ignited to release particles into the clouds. When the events of Operation Popeye were publicised, a ban was put in place by the European Modification Convention to prevent military tactics that controlled the weather.

Silver iodide canisters can be carried through clouds by a plane

Rain rockets

With cloud-seeding technology, we can shoot clouds to make them rain

1 Silver iodide cartridges
Cartridges filled with silver iodide vapour are placed into a rocket launcher.

2 To the clouds
The cartridges can be launched into the clouds via a ground-based rocket launcher or from a plane.

3 Silver iodide
Silver iodide has a structure similar to ice.

4 Droplet formation
The droplets in the clouds that are too small to fall as rain surround the silver iodide.

5 Ice crystals
As the water and silver iodide combine, ice crystals form.

6 Raindrop
The ice crystals become too heavy to remain in the air. As they fall, they melt to become raindrops.

© Getty / Illustration by Adrian Mann

Marine geoengineering

Could these ocean-based systems reverse damage to the climate?

Cloud-whitening towers

The colour of a cloud depends on particle size and composition. Bright-white clouds can be pleasing to the eye, but they also hold another useful property – they can reflect sunlight back into space, along with the heat energy it carries. This concept of cloud-whitening towers aims to brighten clouds to reduce the warming of the planet.

Did you know?
Geoengineering is the intentional manipulation of the environment on a large scale.

1 Floating vessels
The towers are constructed on a fleet of autonomous boats.

2 Sea to sky
Water is pumped from the sea and sprayed into the sky through these towers.

3 Cloud composition
The fine spray of seawater reduces the average droplet size within the surrounding clouds.

4 Light on white
The small droplets in the clouds scatter light, making them appear white. These white clouds reflect more sunlight away from Earth.

Ocean fertilisation

The idea behind this process is to transport carbon dioxide from the atmosphere to the bottom of the ocean. While humans initiate this process, ocean fertilisation relies on the activity of phytoplankton. This proposed plan has been assessed in many experiments, but some scientists are concerned about the large-scale use of this method and its ability to significantly alter ocean ecosystems at different depths.

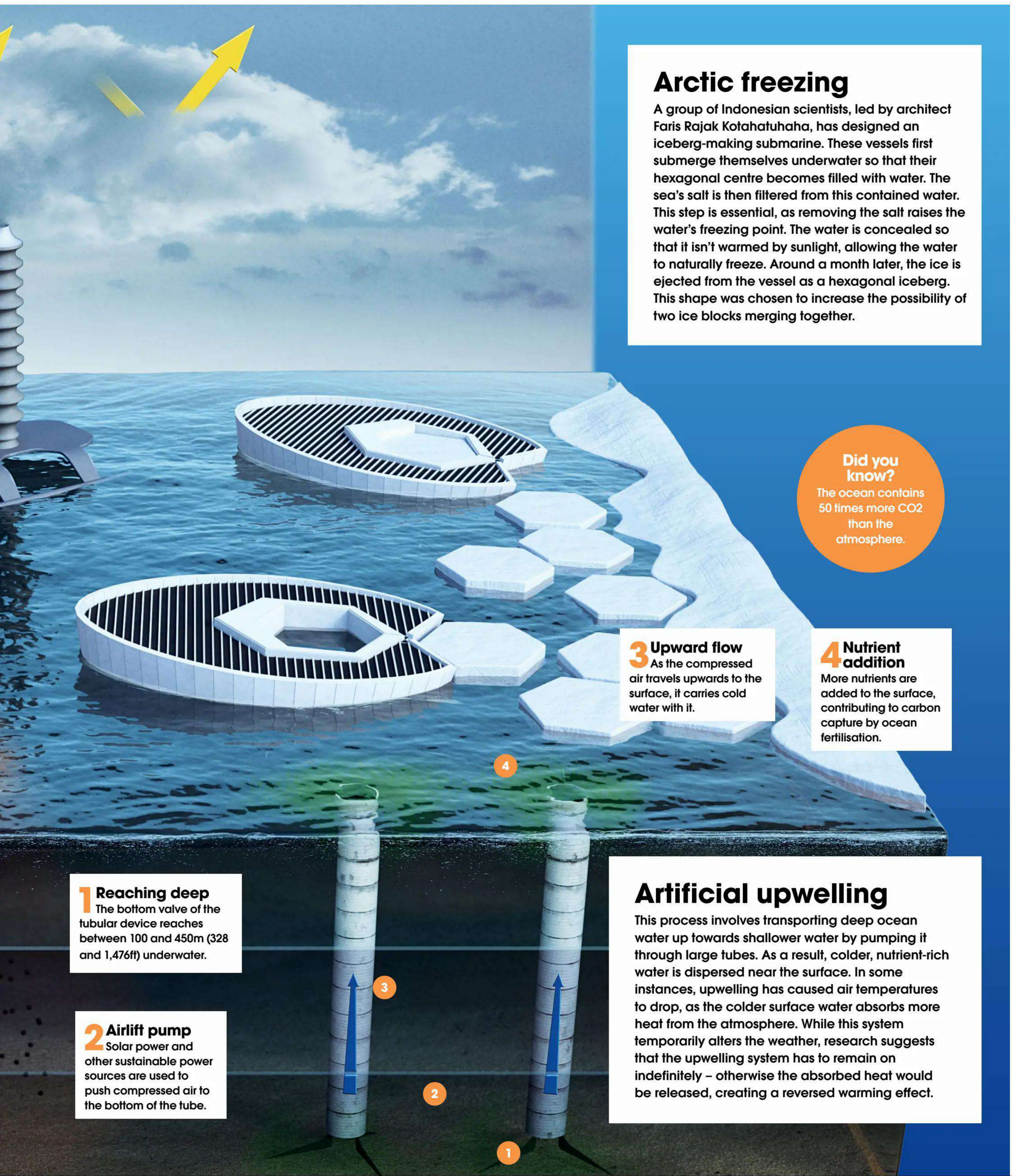
1 Iron offload
Boats release large amounts of iron into the ocean.

2 Phytoplankton
Microscopic marine algae need iron to produce food and grow. Adding iron creates algal blooms.

3 Carbon dioxide absorption
Phytoplankton absorb carbon dioxide from the atmosphere and release oxygen.

4 Sinking CO2
As phytoplankton die, they sink below the surface, carrying the absorbed carbon with them.

5 Locked in the deep
Carbon that's carried into the deep ocean can remain out of the atmosphere for over a hundred years.



Arctic freezing

A group of Indonesian scientists, led by architect Faris Rajak Kotahatuhaha, has designed an iceberg-making submarine. These vessels first submerge themselves underwater so that their hexagonal centre becomes filled with water. The sea's salt is then filtered from this contained water. This step is essential, as removing the salt raises the water's freezing point. The water is concealed so that it isn't warmed by sunlight, allowing the water to naturally freeze. Around a month later, the ice is ejected from the vessel as a hexagonal iceberg. This shape was chosen to increase the possibility of two ice blocks merging together.

Did you know?
The ocean contains 50 times more CO_2 than the atmosphere.

3 Upward flow
As the compressed air travels upwards to the surface, it carries cold water with it.

4 Nutrient addition
More nutrients are added to the surface, contributing to carbon capture by ocean fertilisation.

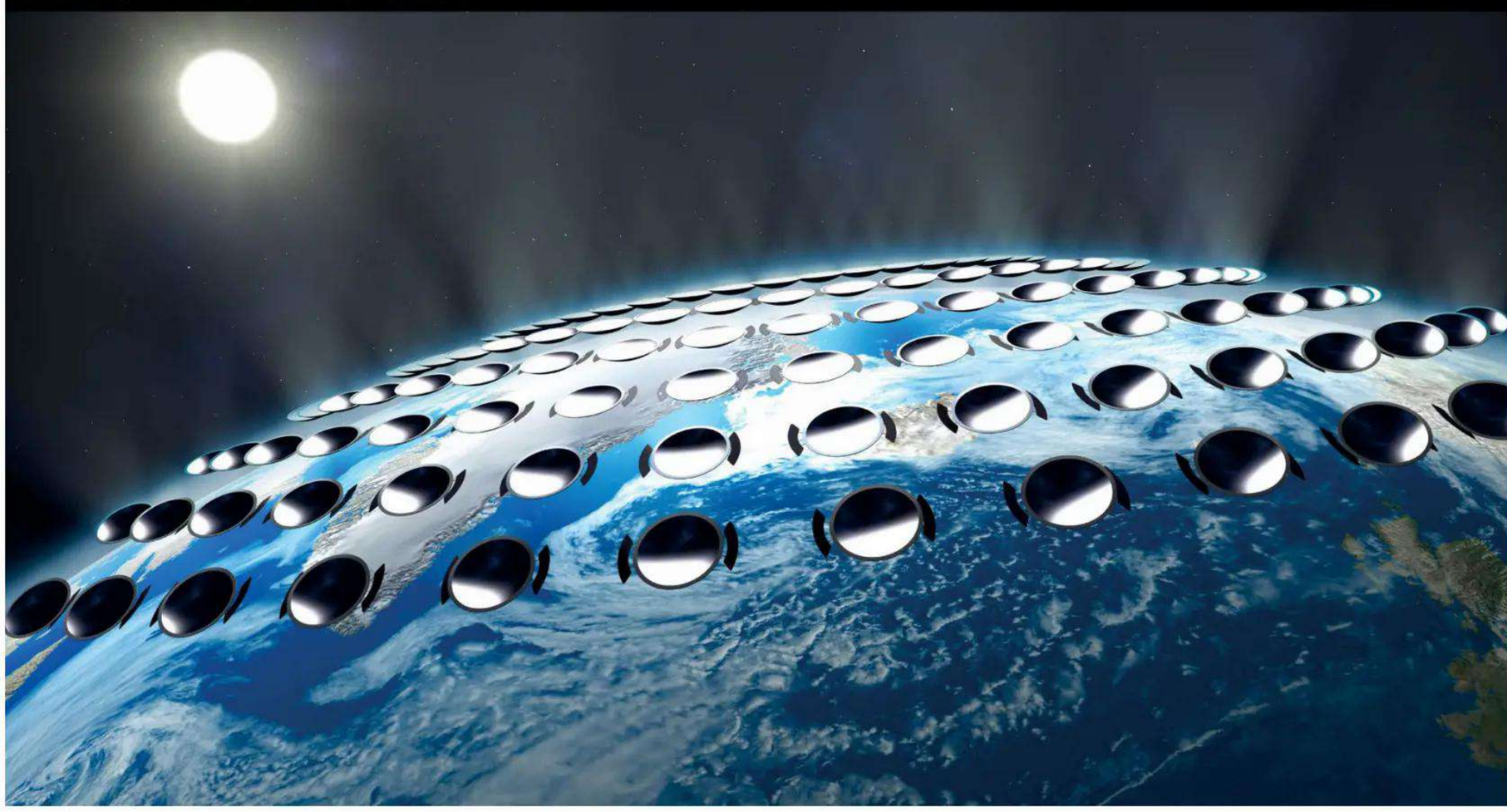
1 Reaching deep
The bottom valve of the tubular device reaches between 100 and 450m (328 and 1,476ft) underwater.

2 Airlift pump
Solar power and other sustainable power sources are used to push compressed air to the bottom of the tube.

Artificial upwelling

This process involves transporting deep ocean water up towards shallower water by pumping it through large tubes. As a result, colder, nutrient-rich water is dispersed near the surface. In some instances, upwelling has caused air temperatures to drop, as the colder surface water absorbs more heat from the atmosphere. While this system temporarily alters the weather, research suggests that the upwelling system has to remain on indefinitely – otherwise the absorbed heat would be released, creating a reversed warming effect.

© Illustration by Nicholas Forder



Multiple small mirror satellites could be gradually introduced to space

Protecting Earth from space

Geoengineering projects are all created to change Earth's climate, but they're not all designed to function on our planet. Space geoengineering involves taking a large step back from Earth in an attempt to make more significant alterations. Entering space means being closer to the Sun, and so much of the geoengineering technology envisaged for Earth orbit involves manipulating the sunlight that illuminates and warms our planet.

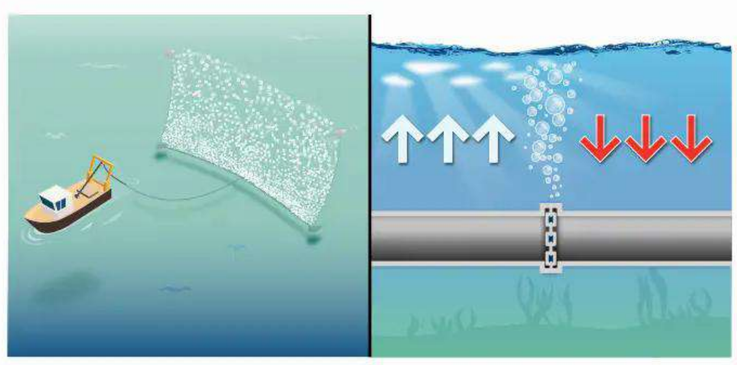
The first idea for this type of space-based technology came from engineer James Early in 1989. His concept involved building a giant glass sheet, around 2,012 kilometres (1,250 miles) in width. When orbiting Earth, this glass structure would serve as a barrier between the Sun and Earth, reflecting sunlight back into space and reducing the radiation that entered Earth's atmosphere. This substantial solid structure would be incredibly expensive to fly into space, and would likely need to be assembled once there. As we currently have no long-term human presence on another planetary body, some of today's scientists have envisaged a more manageable array of smaller mirror satellites and areas of dense asteroid dust to serve as a solar barrier.

To block and deflect light away from Earth, any equipment needs to remain in a stable orbit. The most commonly proposed area to deploy such a system is at the L1 Lagrange point. This point in space is where the forces of the Sun and Earth's gravity on the object balance out, thus limited energy is needed to keep a satellite in position.

Around 13 per cent of Arctic ice is currently being lost per decade

But with a location planned and multiple ideas in progress, why have none of these concepts materialised into real-life systems? Currently, the one factor that could make space geoengineering so successful is also the one that could create the greatest failure – the sheer scale of it. In contrast to the precise locations that can be targeted by a terrestrial system, altering the weather from space focuses on the entire planet. These large-scale adjustments can't be properly tested until the mission has been funded and launched, and nobody can know for sure how the planet would respond to a sudden cooling and reduction in light.

Did you know?
Cloud-seeding has been used in the United States since the 1950s.



Bubble curtains may be able to prevent the warm waters that allow hurricanes to form. An underwater perforated pipe releases bubbles to carry colder water to the ocean surface

5 Ways to monitor the weather today

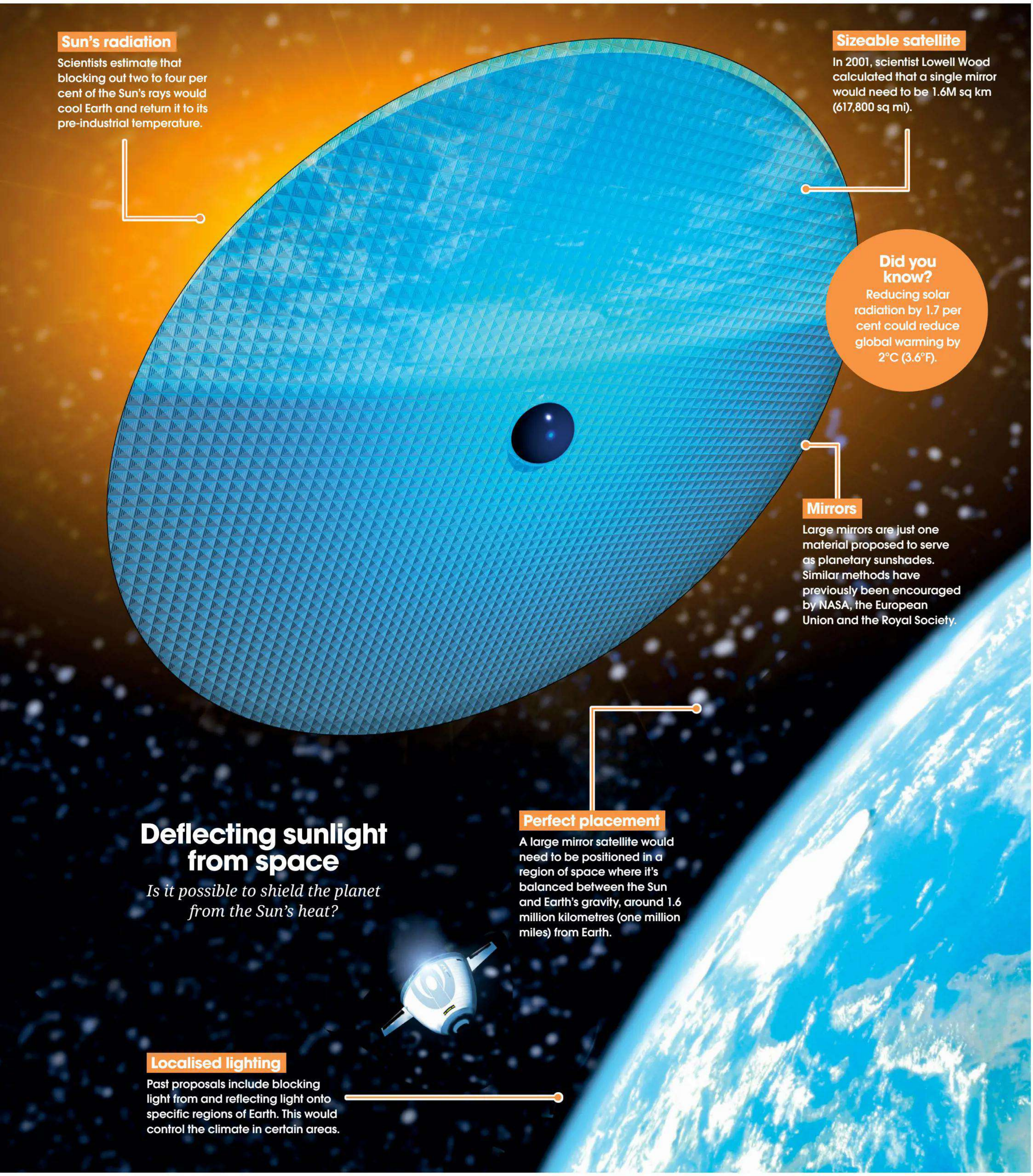
1 Satellite data
Weather satellites orbiting the Earth scan the planet with instruments which measure reflected light and infrared temperatures.

2 Doppler radar
To observe storms, this radar detects different types of precipitation, wind speed and direction and the rotation of storm clouds.

3 Radiosondes
Often carried by weather balloons, radiosondes measure atmospheric pressure, humidity, air pressure and wind speed.

4 ASOS
The Automated Surface Observing System consists of 900 stations across the US. Every hour, these stations measure air temperature, precipitation type and amount, visibility, cloud height and wind.

5 AWIPS
The Advanced Weather Interactive Processing System analyses data from different sensors to make weather predictions. This data enables the visualisations that weather forecasters can share to save lives.



Sun's radiation

Scientists estimate that blocking out two to four per cent of the Sun's rays would cool Earth and return it to its pre-industrial temperature.

Sizeable satellite

In 2001, scientist Lowell Wood calculated that a single mirror would need to be 1.6M sq km (617,800 sq mi).

Did you know?

Reducing solar radiation by 1.7 per cent could reduce global warming by 2°C (3.6°F).

Mirrors

Large mirrors are just one material proposed to serve as planetary sunshades. Similar methods have previously been encouraged by NASA, the European Union and the Royal Society.

Deflecting sunlight from space

Is it possible to shield the planet from the Sun's heat?

Perfect placement

A large mirror satellite would need to be positioned in a region of space where it's balanced between the Sun and Earth's gravity, around 1.6 million kilometres (one million miles) from Earth.

Localised lighting

Past proposals include blocking light from and reflecting light onto specific regions of Earth. This would control the climate in certain areas.

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UNDERSTANDING Meteorology

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Understanding Meteorology First Edition (HIB7003)
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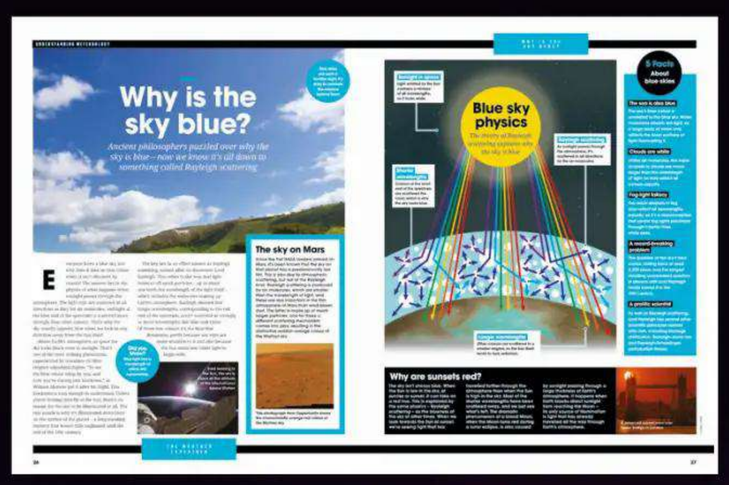

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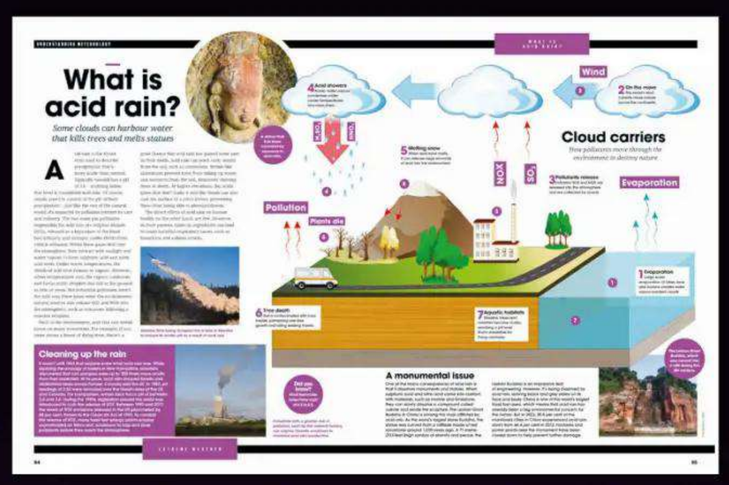

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